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SUPERCONDUCTING ELECTRICAL MACHINERY AS A MEANS OF POWER TRANSMISSION IN AIRCRAFT

By

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The work done under this contract is a portion of the overall project to investigate new ideas and concepts which might offer advantages in future propulsion systems for Army aircraft.

Although electrical drive systems have inherent advantages in flexibility of installation and high reliability, the high weight has prevented their use in aircraft. With the advancement of the practicality of superconductors, it appears that this weight penalty will be sharply reduced.

The advance in fuel cell technology requires research into means of using this potentially effective means of power.

This command concurs in the conclusions arrived at by the contractor.

SUPERCONDUCTING ELECTRICAL MACHINERY AS A
MEANS OF POWER TRANSMISSION IN AIRCRAFT

Final Report

Dynatech Report 620

by

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For

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ABSTRACT

The advantages and limitations encountered in adapting supercon-
ducting electrical machinery to replace the mechanical power transmission
system in aircraft are presented. Major components and system arrangements
are evaluated and compared relative to weight, volume, efficiency, reliability,
readiness, and cost. The superconducting systems when used in high total
power applications are competitive on the basis of weight and efficiency, occupy
a greater volume, but are more reliable when compared with the equivalent
mechanical system.

PREFACE

This report covers a program conducted by Dynatech Corporation, Cambridge, Massachusetts, under Contract No. DA-44-177-AMC-288(T), entitled, "Study of Superconducting Electrical Machinery for Aircraft Application."

Mr. Hugh A. Robinson was principal investigator. The work was performed for the Dynatech Corporation by Mr. John R. Blutt, Mr. Henry W. Mooncai, Mr. Charles J. Oberhauser, Mr. L. Scott Duncan, Mr. Edgar H. Sibley, and Dr. John M. Reynolds.

The work was administered under the direction of the U.S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia. Mr. R. P. McKinnon was the Contracting Officer and Mr. Nelson Daniel the Technical Representative.

This report covers work performed from April 6, 1965, through November 6, 1965.

We wish to acknowledge the suggestions, recommendations and technical assistance received from Mr. Daniel during the the course of this program. In particular, the information provided concerning the construction, operation and control of the present mechanical systems was invaluable to the progress of the program.

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Section 1

SUMMARY

The purpose of this investigation was to determine the advantages and limitations to be expected in adapting superconducting electrical machinery to replace the mechanical power transmission system in aircraft.

The major components of the superconducting system--motors, generators, refrigerators, transmission lines, and speed reducers--were analyzed in detail. The most promising design for each component was used to develop several system arrangements which were evaluated in detail and optimized where possible. The two most attractive system arrangements were compared with an equivalent mechanical system on the basis of relative weight, volume, efficiency, reliability, readiness, and cost.

The most significant results of the design evaluations and comparisons are: (1) superconducting systems are most attractive for high total power applications, (2) superconducting systems in the high power applications are competitive with the mechanical system on the basis of weight, (3) the superconducting systems occupy a greater volume than the equivalent mechanical system, (4) the efficiencies of the mechanical and the electrical systems are comparable, and (5) the electrical systems, having a fewer number of parts, are more reliable and somewhat safer than the mechanical system.

The major state-of-the-art advances required and the major limitations on the adaptability of the superconducting system are: (1) the AC losses in the superconductor indicate a need for further study of new superconducting materials and a better understanding of the loss mechanisms, and (2) the low efficiency and high weight of the refrigerator indicate the need for further study of refrigeration cycles and equipment design.

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Section 2

INTRODUCTION

Rapid progress in cryogenic technology in association with the space program has made available materials, processes, and techniques which, when applied to superconducting electrical machinery, could result in major reductions in the size and weight of such units. This low weight and an acceptable efficiency make superconducting machinery potentially attractive for airborne applications. In particular, one can envision superconducting electrical machinery providing a lightweight power transmission system for helicopters or for tilt-wing-type V/STOL aircraft.

A recently completed study sponsored by the Aeronautical Propulsion Laboratory of the United States Air Force covered the application of super-conductor techniques for electrical generators for space application. The Air Force is extending the generator studies to include investigation of alternating currents. These studies cover generators only; motors are not included. The studies so far have indicated that there are no characteristics of the system that would limit the application to space environment.

Studies conducted by the industry have indicated that the increased current densities possible with superconducting materials permit sharply reduced generator weights. Actually, insofar as weight is concerned, attention is focused on the refrigeration system needed to produce the cryogenic environment required for the superconducting phenomenon, rather than on the generator itself. While such refrigerators are thermodynamically very inefficient, careful attention to the minimization of heat generation sources and heat transfer into the generator yields acceptable refrigeration loads. This permits the design of complete generator packages, including refrigerator, weighing about 0.3 pound per kilowatt (for 1000 kilowatt output). The overall efficiency of the generator, including refrigerator power requirements, is approximately 98 percent.

The subject of this report is directed to the design of a power transmission system based upon superconducting motors and generators which will be competitive with advanced mechanical systems. In addition, those areas in which the present state of the art in superconducting machinery fails to meet the operational performance of the mechanical transmission system will be defined, and those technical developments which are necessary to overcome these deficiencies will be specified.

Section 3 outlines the present state of the art of superconductivity and cryogenic refrigeration, with emphasis on problem areas and possible areas of advancement.

In Section 4 a review of the basic motor types applicable to the subject transmission system is given. Also, a summary of information on cryogenic machines has been included to round out the perspective of the review. Appendix IV gives more detailed information on the field of cryogenic electrical machinery.

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In Section 5 the design concepts of the various components are discussed, as well as the problems inherent in the designs, and a preliminary evaluation of the individual components is made. The results of parametric studies are included which will be used in Sections 6 and 7 for evaluation of various electrical system designs and for comparison with an equivalent mechanical system.

In Section 6, various component arrangements are investigated and compared on a weight basis using the information described in Section 5. Out of the five arrangements studied, two were selected for comparison with an equivalent mechanical system in Section 7. While most of the comparison study of Section 7 is based upon the present state of the art, the effect that advances in the art will have on the comparison is discussed.

Section 3

STATE OF THE ART

3.1 Superconductivity

Superconductivity is a zero-electrical-resistance state exhibited by some materials at temperatures near absolute zero. The technological implications of zero-resistance materials promise high magnetic fields requiring little or no power for their generation, transmission of power with no losses, highly efficient electrical machinery, and even electromagnetic propulsion and shielding from harmful cosmic radiation for space vehicles. Much emphasis has been placed on the study of new materials which are likely candidates of being superconductors and the improvement of currently known superconducting materials with respect to their properties and fabrication on a commercially economical basis.

The zero-resistance realm of superconductors was found to be dependent upon three variables--magnetic field, current, and temperature. For each of the superconductive materials thus far discovered, there is a critical magnetic field strength which identifies the maximum magnetic field in which the superconductor can operate and still remain superconductive. Critical field strengths of presently investigated materials are thought to run as high as 600,000 gauss.

The critical current is the maximum current that a superconductor will carry. Critical currents are very sensitive to metallurgical variables, and manufacturing conditions are usually set to maximize these currents. This requires the testing of a large number of samples to determine optimum conditions.

The critical temperature is the precise temperature at which a material becomes superconductive. The resistance of the material does not simply decrease as a function of temperature; it vanishes completely at and below this temperature and becomes a perfect conductor.

These three variables of magnetic field (H_c), current (J_c), and temperature (T_c) are also functions of each other, as shown in a three-dimensional plot of Figure 1. Superconductivity will not exist outside the bounded volume.

Superconductivity was discovered in 1911, but was of no practical importance for years because most metals became normal again in magnetic fields of only a few hundred gauss. Only in the last few years have a number of alloys and intermetallic compounds such as niobium-zirconium and niobium-tin, which retain their superconducting properties in fields from 50 to 200 kilogauss, been investigated. These materials (known as hard or type II superconductors) differ from the pure metals (known as soft or type I superconductors) in several respects. In particular, they do not exhibit flux exclusion (Meissner Effect), but allow magnetic flux to penetrate into the bulk of the material. Recently, considerable progress has been made in understanding the behavior of these type II superconductors. Several characteristics, such as the variation of critical

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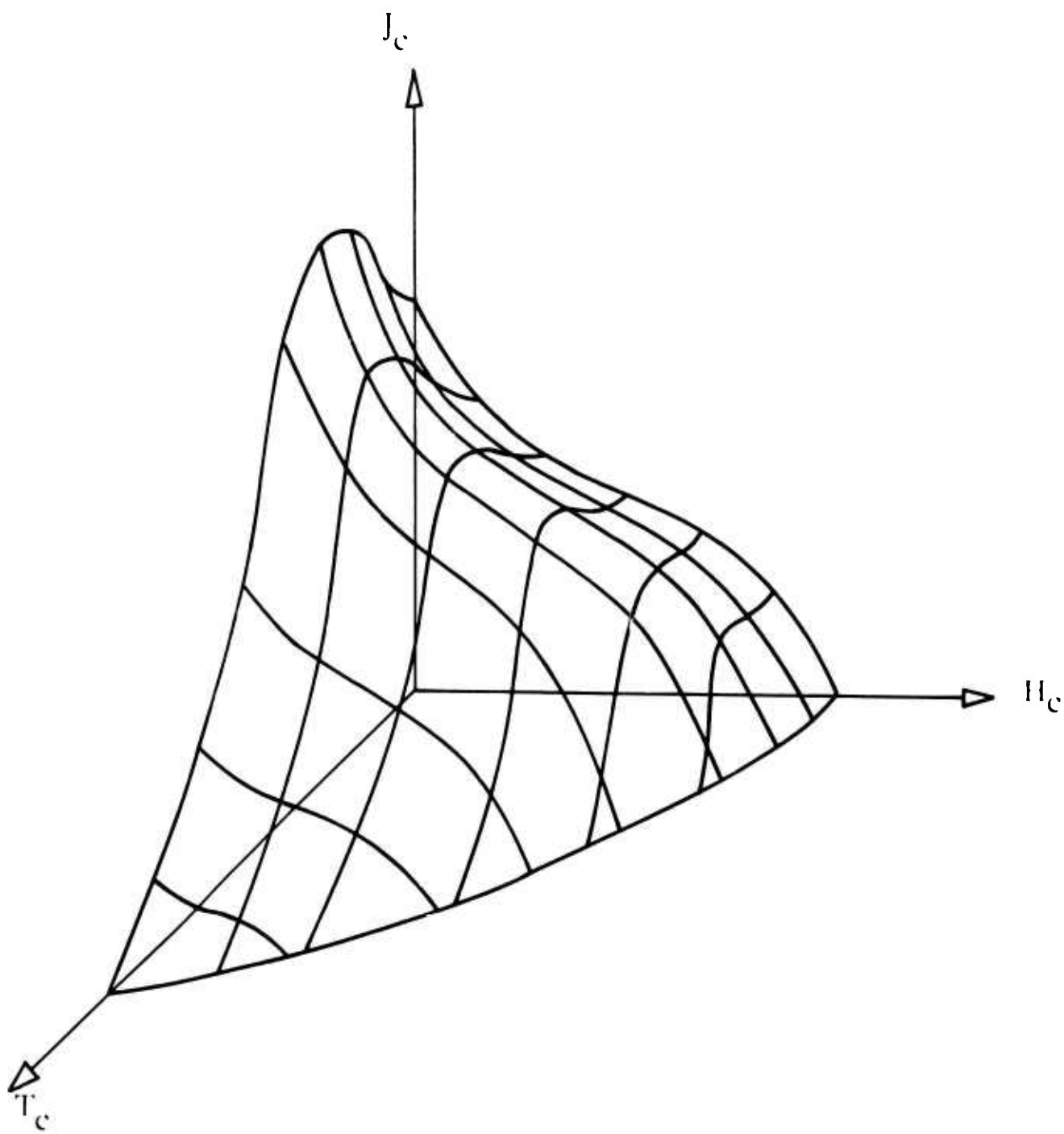
Figure 1. Interdependence of Critical Magnetic Field,
Current, and Temperature of a Typical
Superconductor (Type II)

magnetic field with temperature, can be calculated from the theory developed by Ginzburg, Landau, Abrikosov, and Gorkov [2]. However, several aspects of their behavior cannot be calculated from theory, such as their current carrying capacity, although there is considerable experimental data on the effects of metallurgical processing. In these areas it is still necessary to rely on phenomenological models to explain the properties of superconductors.

There are several considerations which will govern the selection of a material for generator and motor windings:

(1)   The critical field of the superconductor must not limit the design. The critical fields of several type II superconductors are shown in Figure 2 as a function of temperature.

(2)   The critical temperature should be as high as possible in order to minimize refrigeration system weight. The critical temperatures of the most common high field superconductors are shown in Table I. Since the refrigerator weight increases rapidly as the operating temperature decreases, there is a considerable advantage in using an intermetallic compound such as Nb_3Sn rather than the ductile alloys Nb-Zr or Nb-Ti.

(3)   The material should be flexible enough to wind the generator or motor. This requirement is not easily fulfilled by the intermetallic compounds, which are very brittle. The problem was originally solved by forming the compound by the reaction of its constituent metals after mechanical shaping, but since this requires firing temperatures of about $1000°$ C, it is not a very convenient method. An alternative solution, however, is to use thin films of the compound which are sufficiently flexible if they are not more than a few ten-thousandths inch thick. Such films have to be formed on a substrate to give them mechanical strength, and may be formed by diffusion or vapor deposition processes. The ductile alloys can be used to wind the generator and motors without the brittleness of the intermetallic compounds. However, the ductile alloys do not have as high a critical temperature as the intermetallic compounds.

(4)   The current carrying capacity must be high. The average current densities of three types of Nb_3Sn are shown in Figure 3 as a function of the magnetic field.

(5)   The AC losses in the superconductor to be applied to the armature must be low. An important point to bear in mind is that superconductor wires to date have been optimized with respect to DC applications. Type II superconductors
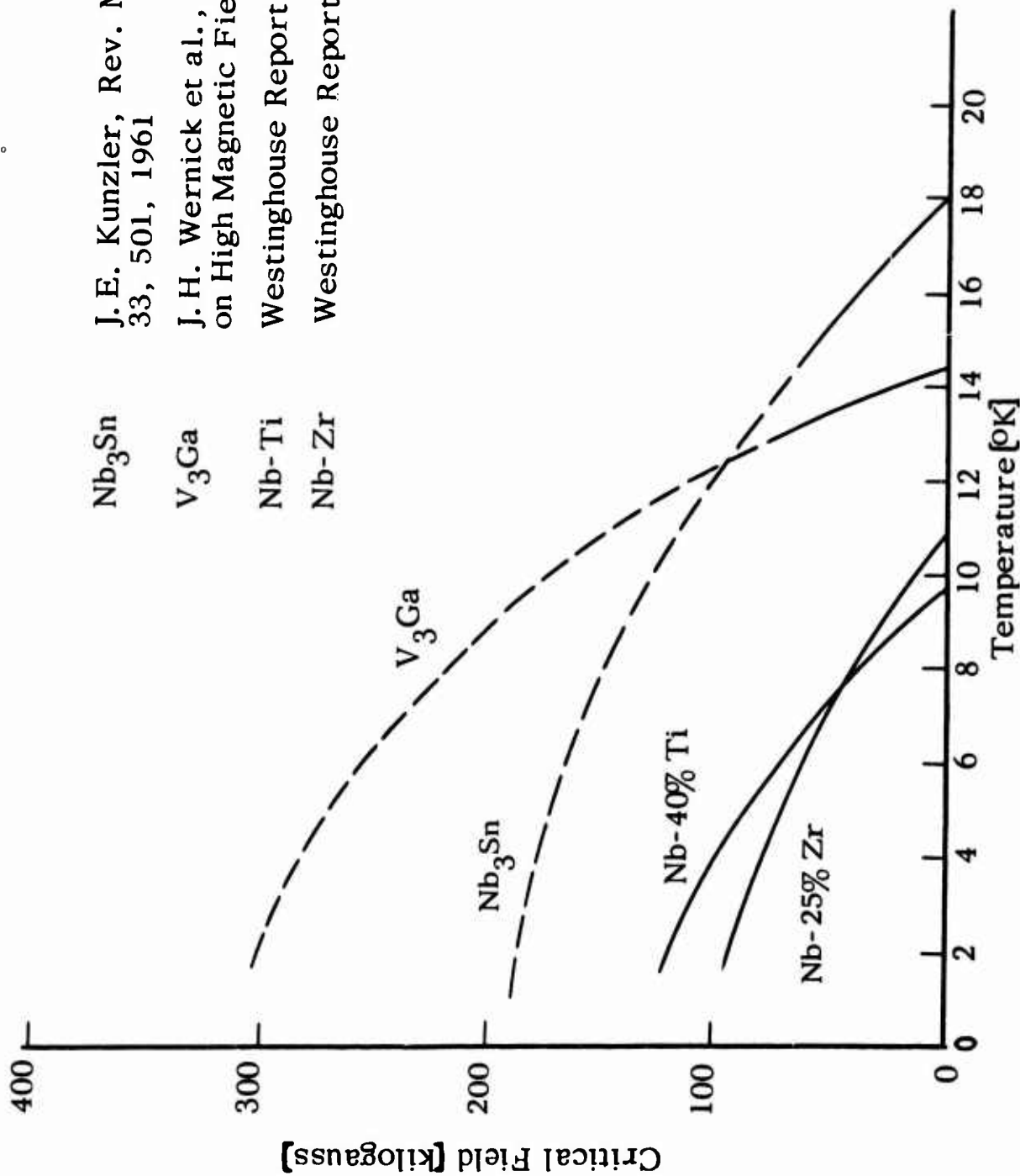
Figure 2. Critical Fields for Various Superconductors

Nb$_3$Sn   J. E. Kunzler, Rev. Mod. Phys., 33, 501, 1961

V$_3$Ga   J. H. Wernick et al., MIT Conference on High Magnetic Fields, 1961

Nb-Ti   Westinghouse Report #63-128-278-P3

Nb-Zr   Westinghouse Report #63-128-278-P3

Table I

Critical Temperatures of Some Superconducting Alloys and Compounds

Superconducting Alloy or Compound	Critical Temperature	Availability
Nb_3Sn	18.0° K	Commercially available
V_3Si	16.8	Laboratory specimen
V_3Ga	14.6	Laboratory specimen
NbN*	14.7	Laboratory specimen
M_oN*	12.0	Laboratory specimen
NbC*	11.1	Laboratory specimen
Nb - 25% Zr	10.9	Commercially available
Nb - 40% Ti	9.8	Commercially available

* Note: The measurements of critical temperature of the nitrides and carbides of transition metals are not reliable, since they depend critically on specimen preparation.

A - Kunzler Wire 0.011" Dia.
(G. E. Research Report #62-RL-3153M)

B - Niostan Ribbon
(Data published by National Research
Corporation, Cambridge, Massachusetts)

C - Vapor Deposited Ribbon
(RCA Paper at 1962 AIME Conference)

* Current divided by total cross section
of wire, including substrate

Average Current Density* [10^5 amp/cm^2]

Field [kg]
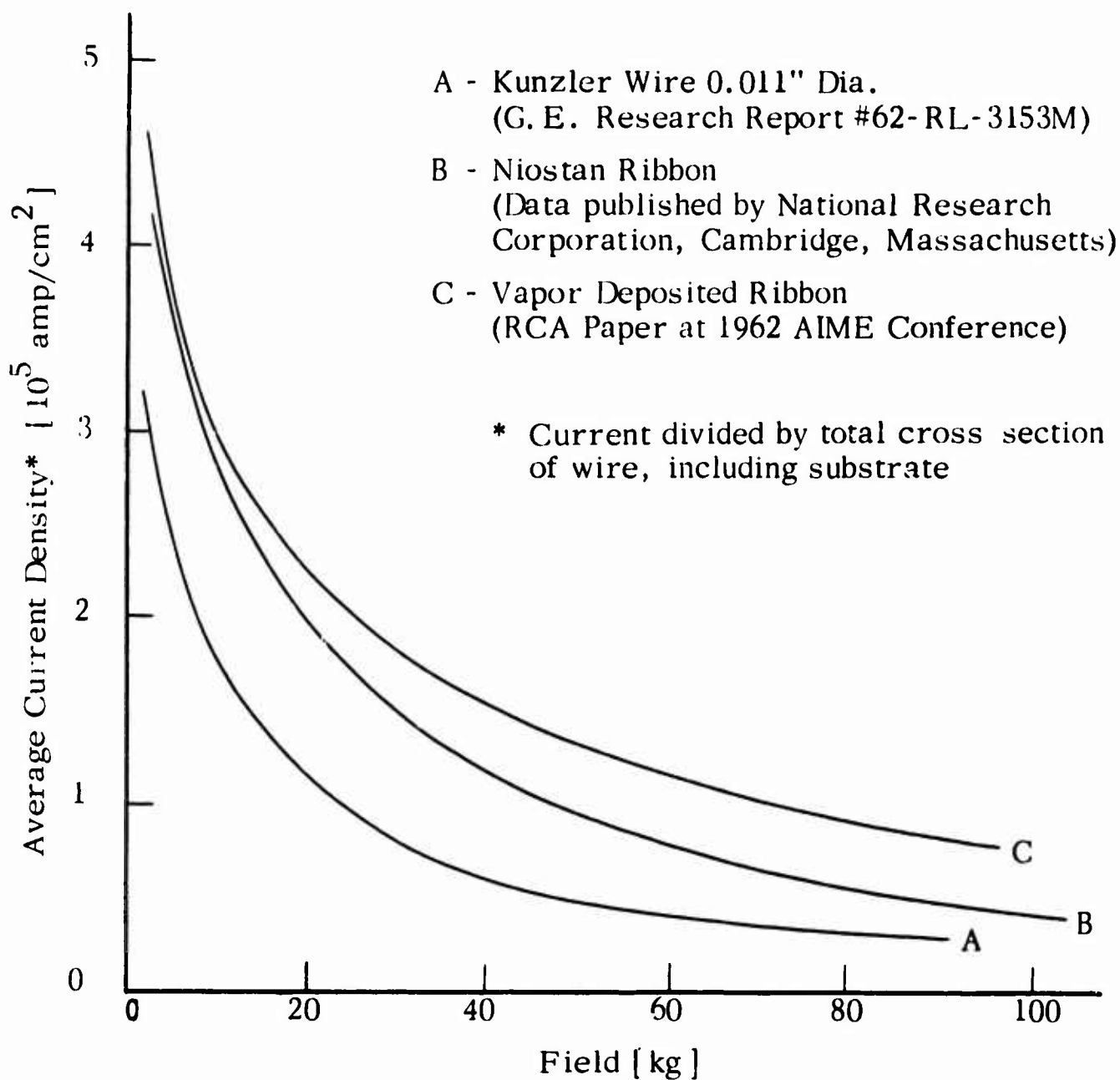
Figure 3. Average Current Density in Nb$_3$Sn
Wires at 4.2^{o}K

exhibit a hysteresis-type behavior when subjected to a varying magnetic field or when carrying an alternating current. This irreversible phenomenon gives rise to a heat dissipation from the superconductor--a departure from zero resistance. The hysteresis energy lost per cycle is equal to the area enclosed by the hysteresis loop. This loss has been calculated by H. London [3] and also by Hart and Schmitt [4]. Since this loss is a function of the superconductor thickness, thin films have considerable advantage in reducing this loss. For alternating field applications such as the armature of the motor or generator, it is very likely that new arrangements of existing materials or even new materials will emerge to reduce this loss to a negligible level.

The extent to which superconductors will be used in motors and generators depends largely on developments in the following areas:

(1) Lower AC losses
(2) Higher critical temperatures
(3) Higher current densities
(4) Better handling characteristics of the material
(5) New concepts of superconductivity

Present levels of critical magnetic fields are entirely sufficient for motor or generator applications.

AC losses are very important in superconductor generators or motors since they are by far the largest source of heat generation in the cryogenic region. Lower losses would lower the requirements of the refrigerator load considerably. Much effort has been focused on identifying the mechanism of AC losses (Refs. 3 through 10). Since this loss is a function of the superconductor thickness, commercial manufacturers have concentrated their efforts in making thin layers of Nb3Sn by depositing thin films on a supporting substrate in the form of a ribbon or a wire. In some cases, many fine strands of superconductor are twisted together to form a cable. Much more work is required to produce still thinner films and finer strands. Much of the thin film technology is presently being developed by the superconducting digital computer memory manufacturers.

A continuing search for new superconducting materials has been conducted since 1954 by Matthias [11]. Roberts [12] has tabulated known superconductors. These studies are aimed at discovering materials with higher critical temperatures as well as other properties (current, field, losses, etc.) to improve device performance. The advantages from refrigeration alone, of a material having a critical temperature above 30° K, are sufficiently great to warrant a considerable effort to raise the level of critical temperature. The present ceiling is 18° K for Nb3Sn. Many commercial superconducting wire manufacturers are developing proprietary wire configurations and processes which afford greater performance stability and thermal characteristics.

The possibility of superconductivity existing at room temperature would open up vast vistas of applications, since the refrigeration required for operation at low temperatures has been the major obstacle. Although it has not yet been achieved, theoretical studies [13] suggest that it is possible to synthesize materials that, like certain metals at low temperatures, conduct electricity without resistance. Little[14] states that certain organic molecules should be able to exist in the superconducting state at temperatures as high as room temperature (about 300° K) and perhaps even higher! This possibility may appear to be a long time away; however, Soviet physicist and theoretician Abrikosov has indicated that the future of superconductors lies in thin films and has hinted that the Russians are trying to develop a room-temperature superconductor made of thin film [15].

3.2   Cryogenic Refrigeration

3.2.1   Introduction

The weight, reliability, and performance of a superconducting transmission system will be greatly dependent upon the refrigeration unit. For a typical system, the refrigeration unit may be as much as 50 percent to 70 percent of the total transmission system weight. Consequently, it is essential that the present state of the refrigeration art and possible future developments be investigated in some detail to estimate the influence of the refrigerator on the total system.

Cryogenic refrigerators and gas liquifiers are not new--some were made before the turn of the century. There are many large gas liquifiers in operation in this country today and many more under construction. Arthur D. Little, Inc., has sold more than two hundred of their laboratory helium refrigerators and liquifiers in the past 18 or 20 years. Because of this backlog of experience, some facets of the performance of cryogenic refrigerators are well defined; for example, the coefficient of performance.

However, aerospace requirements have accelerated progress and shifted emphasis in some areas. New and improved operating cycles are being used. When these are fully developed, further increases in coefficient of performance may be realized, particularly for refrigerators operating below 30° K. Another area receiving extensive attention is weight reduction. Most cryogenic refrigerators made to date are either large fixed installations or laboratory machines. These are heavy because there has been little incentive to reduce weight. However, the increasing number of airborne and aerospace applications for cryogenic refrigerators has led to the design of lightweight machines. Unfortunately, these refrigerators are yet to be built and tested in a sufficient range of capacities and cold-end temperatures to permit accurate evaluation of weight from experience. Therefore it is necessary to rely on design study weights for the next generation of refrigerators.

3.2.2   Specifications

In the application of superconducting electrical machinery for power transmission in aricraft it is, in general, required that the refrigeration

maintain a cold-end temperature of approximately 10° K under relatively high heat loads. For reasons of economy it is also desirable that a large portion of the heat losses into the system be removed at a higher temperature, say, 80° K. All heat rejection from the system is assumed to occur by forced convection in a refrigerant-to-atmosphere heat exchanger. Ambient temperature is assumed to be 300° K.

3.3.3 Thermodynamic Cycles

Due to the high heat loads, gas-expansion closed-cycle refrigeration systems look most promising for this application. Other methods or refrigeration, such as thermoelectric cooling and adiabatic demagnetization, are inherently less efficient and would impose too large a weight and performance penalty on the overall system. See Reference 16 for a description and evaluation of these and other refrigeration techniques.

The only gas which can be used as a refrigerant below 12° K is helium. Since it will not be necessary to cool the helium below its saturation temperature, two-phase flow and its associated problems will not be encountered.

There are several types of low-temperature helium refrigerators in use at the present time. Most of these are based on one of four thermodynamic cycles. These are the Joule-Thomson Expansion Cycle, Claude or Expansion Engine Cycle, Stirling Cycle, and Gifford-McMahon Cycle. These cycles have been discussed extensively in the cryogenic refrigeration literature (Refs. 16 through 33).

Although it is theoretically possible to use each of the above cycles for this application, it is our opinion that the only practical choice is the Expansion Engine Cycle. This opinion is based on the following limitations of the other cycles:

Joule-Thomson Expansion Cycle

This cycle is normally utilized when it is necessary to liquify the working fluid. When it is unnecessary to liquify the gas, as in this case, the low efficiency of this cycle compared to the Expansion Engine Cycle results in an unacceptable power penalty.

Stirling Cycle

This cycle requires the use of reciprocating components which present extreme lubrication and wear problems. A satisfactory solution to this problem does not appear very promising for the near future. In addition, the Stirling Cycle requires the use of a regenerator. A low temperature limit which would appear to be above 12° K is imposed by the regenerator. Therefore, a secondary loop would be required both to achieve the desired temperature and

to provide a cooling medium, since the nature of the Stirling Engine does not allow the working fluid to be used as a cooling medium. This would unncessarily complicate the system and decrease reliability.

Gifford-McMahon Cycle

This cycle, which also requires the use of a regenerator, is inherently less efficient than either the Stirling Cycle or the Expansion Engine Cycle. In addition, it also would require the use of reciprocating components, as does the Stirling Cycle. This leads to the same limitations mentioned for the Stirling Cycle.

Expansion Engine Cycle

An ideal Expansion Engine Cycle is reversible and consists of adiabatic expansion and compression processes connected by constant pressure processes. Heat is transferred from the high-pressure gas entering the expansion engine to the low-pressure gas leaving the expansion engine in a countercurrent heat exchanger. Refrigeration is produced by the expansion of the gas, with the resulting work being merely a by-product. Heat is rejected from the cycle at the high temperature by the compressor coolers. In the practical Expansion Engine Cycle, losses are incurred which result in lower efficiency than in the ideal cycle. These losses arise from irreversibilities of the practical cycle, fluid friction, mechanical friction, gas leakage, and heat leakage.

A temperature-entropy diagram of the Expansion Engine Cycle is shown in Figure 4. The cycle contains two expansion engines and supplied refrigeration at two temperature levels. The use of two expansion engines providing refrigeration at two temperature levels, rather than one expansion engine supplying all the refrigeration at the lower temperature, significantly reduces both the weight and the power requirements for this application. The addition of a third expansion engine would reduce the weight and power requirements still further; however, the effect of adding a third expander is considerably less than that of adding a second expander. For this application, the improved performance that would result from the addition of a third expander appears to be insufficient to warrant the added complexity and reduced reliability incurred.

Analysis and optimization of the cycle must take into account the various types of compressors, expansion engines, and heat exchangers that can be used. Performance, weight, and reliability must all be considered in selecting various types of components.

A weight penalty due to the power consumption of the refrigeration system must also be taken into account in optimizing the cycle. This weight penalty is in the form of additional primary power system weight required to provide the power to operate the refrigerator.

3.3.4 Compressors and Compressor Power

For the heat loads of this particular application, the possible range of flow conditions is such that three types of compressors can be considered.

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These are low-speed reciprocating compressors, high-speed multi-staged re-generative compressors, and high-speed multi-staged centrifugal compressors.

The efficiency of a reciprocating compressor would be quite high. However, the low speed of the reciprocating compressor results in a heavy compressor drive. Lubrication also presents a problem with reciprocating compressors. If oil lubrication is used, then oil removal equipment must be added to the system to prevent contamination of the helium. The oil removal system can add considerable weight to the system. Non-lubricated compressors can be used. The life of a nonlubricated compressor, while significantly less than that of a lubricated compressor, might be adequate for this application.

High-speed multi-staged regenerative compressors utilizing gas bearings offer high reliability and long life. Because of the high speed required for operation of this type of compressor, both the compressor and the drive weight are considerably lower than those of a corresponding reciprocating compressor. The performance of the regenerative compressor, however, is only half as good as that obtainable from the other two types. This results in high power requirements and correspondingly high power weight penalties.

High-speed multi-staged centrifugal compressors utilizing gas bearings offer high reliability, long life, high performance, and low compressor and compressor drive weight. The major difficulty with the centrifugal compressor for this application is the high speed required and the large number of stages. However, taking all factors into consideration, the centrifugal compressor appears to be the best choice.

Compressor performance and size are determined by specific speed considerations based on the relationships presented in References 34 and 35. The maximum speed is limited to 100,000 rpm, which is within the present state of the art for gas-bearing-supported compressors. The maximum tip speed of the compressor rotor was limited to 1500 feet per second by stress considerations.

The high speed of the compressor lends itself well to direct coupling to a small auxiliary-power gas turbine engine, thus eliminating problems of gear drives.

3.3.5 Expansion Engines

Both reciprocating and high-speed turbo-expansion engines have been used in cryogenic refrigerators. Reciprocating expansion engines offer high efficiency but present reliability and lubrication problems. High-speed turbo-expanders offer greater reliability and longer life when gas bearings are utilized. For the flow conditions of this applications, turbo-expanders, while not as efficient as reciprocating expanders, offer satisfactory efficiency. High-speed turbo-expanders appear more suitable for this application for their higher reliability and longer life.

Performance and size of turbo-expanders are given in data presented

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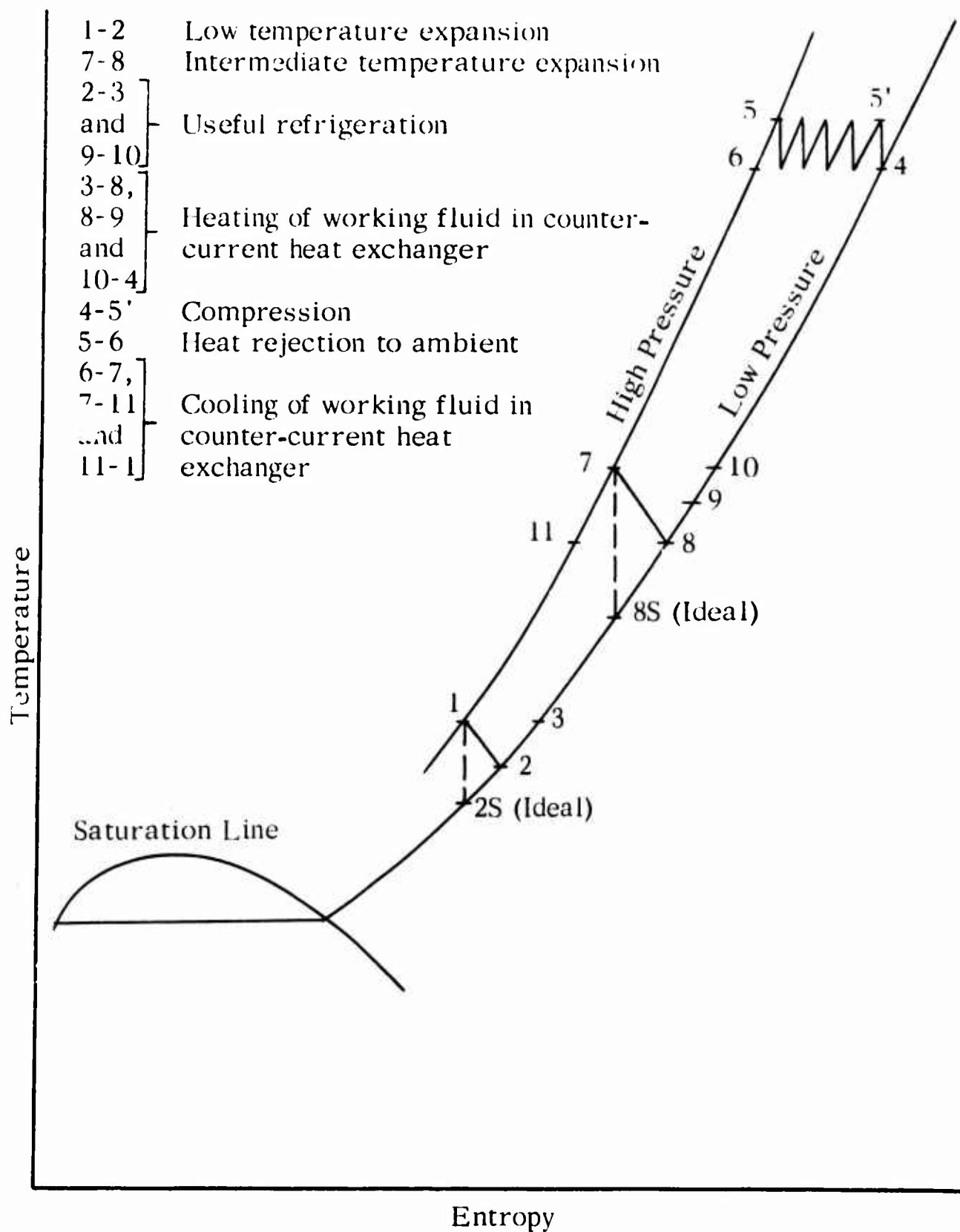
Figure 4. Temperature-Entropy Diagram for Expansion
Engine Cycle

1-2   Low temperature expansion
7-8   Intermediate temperature expansion
2-3
and   ⎱ Useful refrigeration
9-10   ⎰
3-8,
8-9   ⎱ Heating of working fluid in counter-
and   ⎰ current heat exchanger
10-4
4-5'   Compression
5-6   Heat rejection to ambient
6-7,
7-11   ⎱ Cooling of working fluid in
...nd ⎰ counter-current heat
11-1   exchanger

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in References 36, 37, and 38. These references present data for helium turbo-expanders operating at speeds as high as 500,000 rpm. The turbo-expanders are of a radial in-flow type.

3.3.6 Heat Exchangers

Helium-to-helium and helium-to-air heat exchangers are required for intra-cycle and for heat rejection heat transfer, respectively. Compact heat exchangers of the plate fin type (see Refs. 21 and 39) offer ruggedness and low weight with high heat transfer rates and low pressure drops. The counterflow configuration is the most effective for the helium-to-helium heat exchangers. For the heat rejection heat exchanger, use of the cross-flow configuration minimizes the header problems and gives the best overall results. An auxiliary fan is required to guarantee sufficient cooling air flow under all conditions.

3.3.7 Performance and Weight

A gas expansion refrigerator is simply a heat engine in which mechanical work is used to compress a gas; the heat of compression is then rejected, and refrigeration is produced by expansion of the gas. The coefficient of performance (COP) of a refrigerator is defined as the ratio of refrigeration produced (q_0) to the net work input (W_R). The maximum theoretical coefficient of performance of an ideal reversible refrigerator taking in heat at a low temperature (T_C) and rejecting heat at a higher temperature (T_H) can be determined for a Carnot cycle. The coefficient of performance for a Carnot cycle is given by

$$COP = q_0/W_R = \frac{T_C}{T_H - T_C}$$

This relationship represents the maximum attainable performance of a refrigerator and can be used as a reference of comparison for the less efficient practical refrigerators. The rapid decrease in attainable refrigeration performance at lower temperatures is apparent from this relationship.

In a practical cycle the actual performance will be significantly less than that of the ideal Carnot cycle. Reference 18 indicates that the performance of a refrigerator operating at the temperature of 12° K will be only 2 percent to 10 percent of Carnot performance.

Figures 5 and 6 show the reciprocal of the coefficient of performance and the specific weight, respectively, of cryogenic refrigerators as a function of cold-end temperature and refrigeration capacity. As might be expected, 1/COP and specific weight both increase as the cold-end temperature decreases. Decreasing capacity has the same effect due to manufacturing tolerances and limitations as components become very small.

Figures 5 and 6 were compiled on the basis of available information on existing refrigeration systems and design studies (Refs. 16, 18, 21). Particularly in the case of the high capacity systems, of primary interest for this investigation, there is little or no actual experience. Both figures are, therefore, essentially projections and in most instances represent values better than currently available machines. For example, 1/COP is about 15 percent lower at 100° K and 50 percent lower at 4.2° K than present operational refrigerators. The specific weight is also projected lower to reflect the changeover from reciprocating compressors and expansion engines to turbo-centrifugal machines.

The impact that the refrigeration system has on the weight, reliability, and operation of the superconducting electric transmission system has been stressed. Advancements in the state of the refrigeration art can therefore be expected to have a similar impact on the improvement of such a transmission system. While true breakthroughs are, by definition, not predictable, the general improvement in design, manufacture, and operation of machines and systems can be anticipated to some extent.

Continued effort in the design and manufacture of turbo-expanders and compressors can be expected to result in improved overall performance and efficiency. It can be expected that within the next 10 years, a 20-percent improvement in turbo-compressor efficiency is possible.

Efforts are also continuing in the area of compact heat exchangers, where advances in materials, fabrication techniques, and new designs can be expected to increase the effectiveness and reduce the weight.

For the period between 1965 and 1975, an estimate of 20-percent increase in refrigerator coefficient of performance and of 15-percent decrease in system weight appears attainable.

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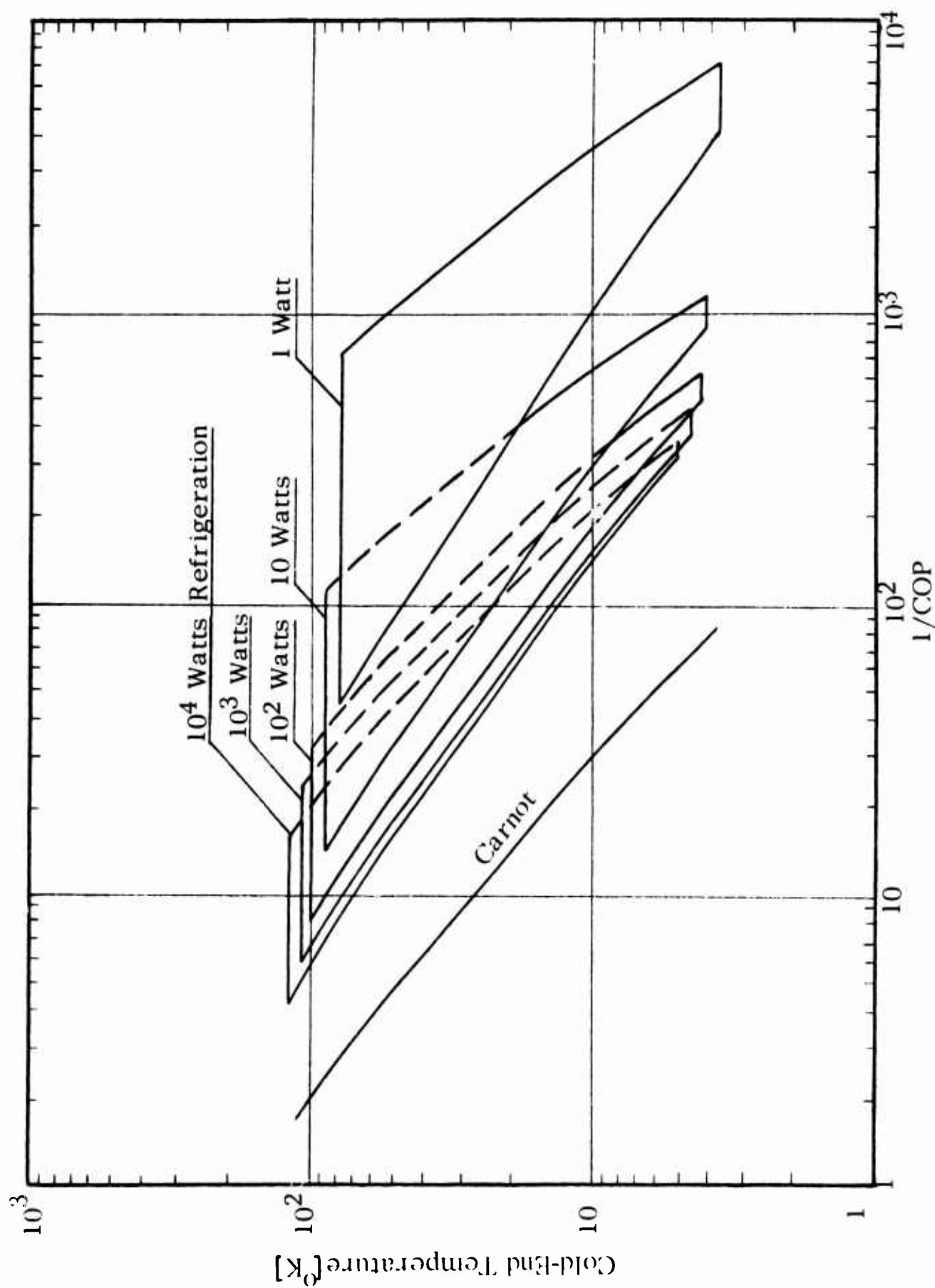
Figure 5. Refrigerator Performance

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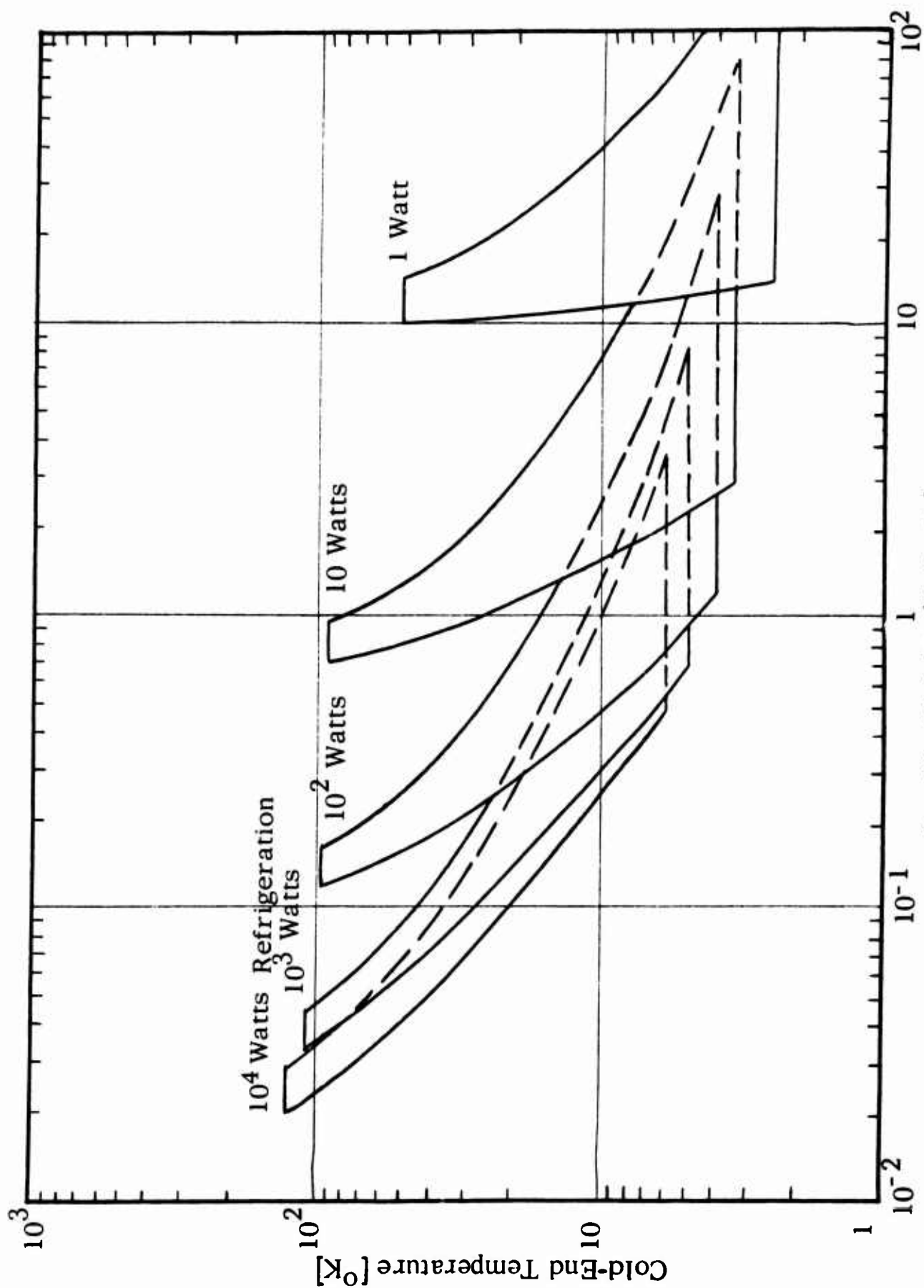
Figure 6. Refrigerator Weight

Section 4

REVIEW OF MOTOR TYPES

4.1 Introduction

Over the years there has been continuous progress in the direction of decreasing the size and weight and increasing the efficiency and reliability of electric motors and generators. Major advances in this direction have been improvements in insulation and design configuration which have resulted in an increase in the rate of heat dissipation from the machine. A consequence of this increased dissipation has been lower operating temperatures, thereby reducing the operating losses or increasing the allowable current density. The unique properties of superconductors (see Section 3.1) immediately suggest that machines wound with these materials may result in extremely compact, efficient devices. It is also likely that these unique properties may present new design concepts and new machine configurations more attractive than conventional configurations.

A study by R. L. Mela, et al, [40] evaluates a number of machine designs, both unique and conventional. The conclusion reached was that the best machine is a DC-excited, more or less conventional design machine, without an iron magnetic path and with both the rotating field and the stationary armature superconducting. The machines investigated in this study were permanent magnet cylindrical and axial air-gap machines, DC-excited cylindrical air-gap machines, inductor and Lundell machines, and an AC-excited electromagnetic machine.

As an extension of the previous work, the machines to be examined here are DC-excited axial air-gap machines, DC-excited cylindrical air-gap machines with and without an iron magnetic path (including a Graham ring, toroidal-wound armature machine), mixed machines (part superconducting, part normal conducting), and cryogenic machines.

Before proceeding with the discussion of these AC machines, a word about DC machines may be in order. The most significant feature differentiating a DC machine from an AC design is the fact that the DC machine has a segmented commutator on the rotor. If the armature, typically of high current to take advantage of the superconductor, is on the rotor, the commutator must be very large to carry the high current (on the order of 50 amperes per square inch). Arcing is a problem and leads to brush heating and short brush life.

With the field on the rotor, the current is decreased to take advantage of the high critical flux density of the superconductor, but many turns are required to generate the strong field. The inductance of such a field is high. Extremely high voltages are generated as the commutator breaks the circuit. The high voltages necessitate extra insulation and lead to arcing and reduced brush life.

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Another factor common to both of the above situations is that ordinary carbon brushes chatter, even under the best of conditions, leading to a distorted waveform and losses in the superconductor.

From the above discussion it would appear that except in some particular situation, or for a very unusual design, the use of superconductivity in a DC machine is of no particular advantage.

4.2   DC-Excited Axial Air-Gap Machine

One particularly important use of superconducting windings is in the creation of magnetic fields with extremely high magnetic flux densities. The axial air-gap machine offers the possibility of high flux density and very efficient use of the field, since the length of the return path relative to the active path, particularly for a multi-stage machine, can be made very small. The axial air-gap machine is shown schematically in Figure 7.

The two major problems in the axial air-gap machine are: (1) finding a winding pattern which provides for efficient use of the total length of conductor and (2) designing a rotor which will contain a large number of conductors and still be structurally sound. Once a satisfactory winding form is found, virtually any power level can be attained by adding more stages.

The problem of winding is that the active lengths of the winding run radially, and there is extreme bunching and interference of the windings near the center of the machine. As the successive windings are pushed farther out to reduce bunching, their active length shortens and they become less effective. Another problem is the high tensile load on the radially oriented conductors on the rotor, resulting from the centrifugal force.

Preliminary calculations indicate that the axial air-gap machine would be about twice as heavy as an equivalent cylindrical air-gap machine in the 3000-horsepower size. Also, a greater length of superconductor would be required to make up for the inefficient winding pattern, and this would lead to greatly increased losses.

4.3   DC-Excited Cylindrical Air-Gap Machines

The majority of conventional motor designs are of the cylindrical air-gap type. When designed to use superconducting windings, it is desirable to wind the armature on the stator with the field on the rotor. In a conventional machine, sliprings and brushes are used to provide a rotating contact to excite the rotor electromagnet. These have not proven to be sufficiently raliable for use with superconducting fields, particularly at high rotational speeds. The most attractive alternative is to use liquid-contact brushes.

Cylindrical air-gap machines can be classified in three major styies: (1) conventional wound without an iron magnetic path, (2) conventional wound with an iron magnetic return path, and (3) Graham ring or toroidal wound. The distinction between (1) and (2) is based upon the operating specifications, being a

Figure 7. Axial Air-Gap Machine
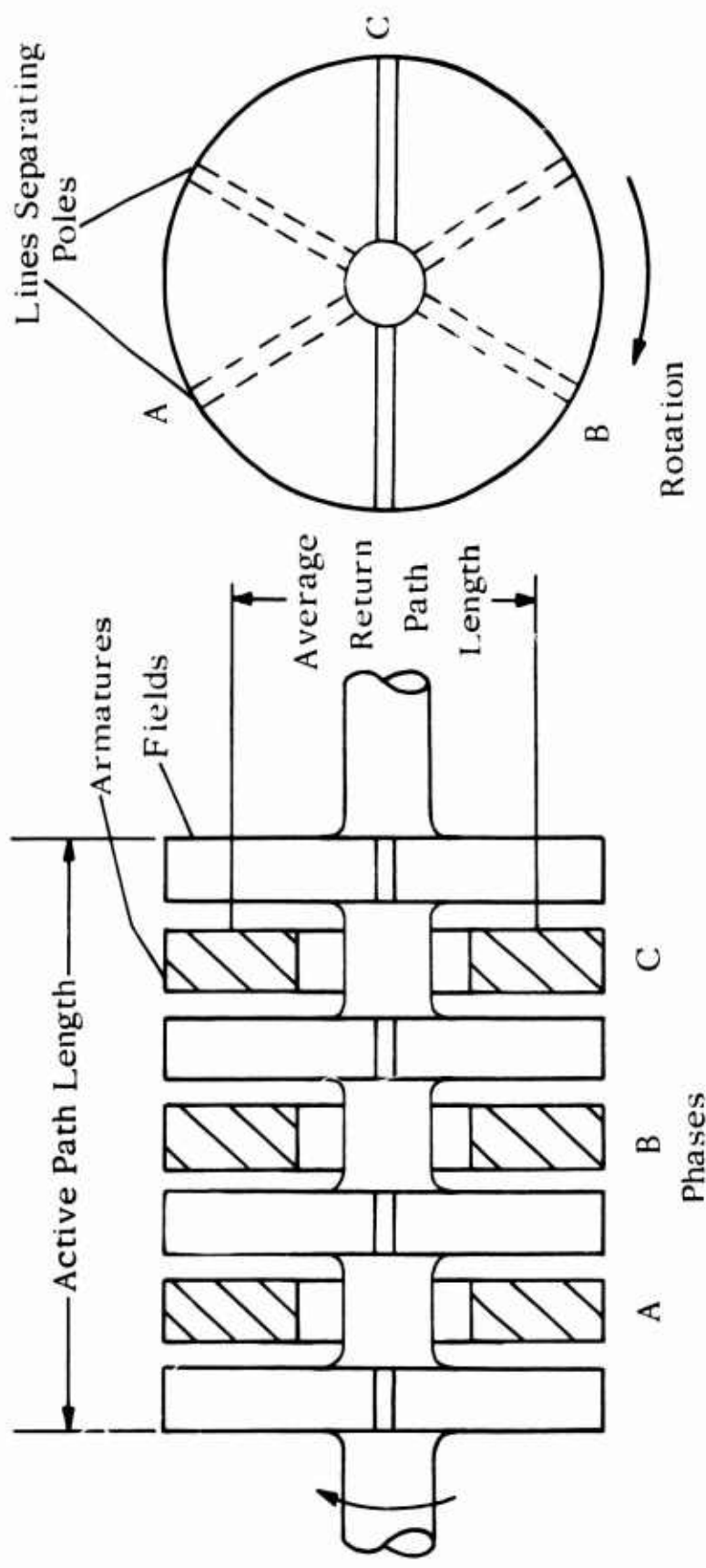
Note: Represents Single-Stage, Two-Pole Machine

trade-off between the various loss mechanisms. The distinction between the conventional wound machines and the toroidal wound machine is a matter of ease of fabrication, support of the windings, and heat transfer between the superconducting windings and the cryogenic cooling fluid.

As explained in detail in the design sections of this report, the major thermal losses in these machines are the windage or fluid friction losses and the losses associated with the alternating currents and magnetic field. In very high-speed machines, the windage losses can be quite significant. By using iron in the magnetic path, the required magneto-motive force (MMF) in the field is decreased, thereby allowing a reduction in the rotor diameter and consequently a reduction in windage losses. The eddy losses generated in the newly added iron magnetic path would seriously overload the low-temperature (10° K) refrigeration. However, by proper design, the iron can be isolated thermally and cooled at an intermediate temperature (80° K) where such cooling is more economical.

As the design speed of the machine is reduced, the windage losses decrease rapidly. A point is reached where it is no longer necessary to require minimizing the rotor diameter, at which point it is better to remove the iron, accept a slightly higher windage loss in the 10° K region, but eliminate the iron loss entirely.

In Section 3.1 it was stated that the intermetallic compounds, those most attractive for electrical machinery because of their electrical, magnetic, and temperature characteristics, are brittle and difficult to handle. Attempts to make them more manageable by depositing them as thin films on ribbon or wire substrates have been reasonably successful; however, even the thin film superconductors are delicate. In a conventionally wound device with its multitude of crossed end loops (Figure 8a), the possibility of damaging the superconductor during winding is high. Also, it is necessary to firmly support the end windings against the magnetic forces encountered during operation and to electrically insulate the wires from each other. But to do so makes it very difficult to cool the windings properly.

The Graham ring or toroidal winding arrangement (Figure 8b) eases the fabrication and cooling problems significantly; there is a minimum of wire crossing, the only electrical insulation required is between successive turns and therefore of low potential, and the end loops are tightly wound on the form and therefore require no additional support. The major disadvantage of this winding is that there is only one active length of wire per turn (there are two in the conventional winding), and therefore the total length of superconductor is increased appreciably. This in turn may lead to an increase in the AC losses for the winding.

4.4   Mixed Machines

Two of the major losses in the superconducting motor/generator system are the windage (viscous drag) losses and the AC losses. By operating the armature at room temperature and cooling only the field, both of these

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Conventional Winding

(a)
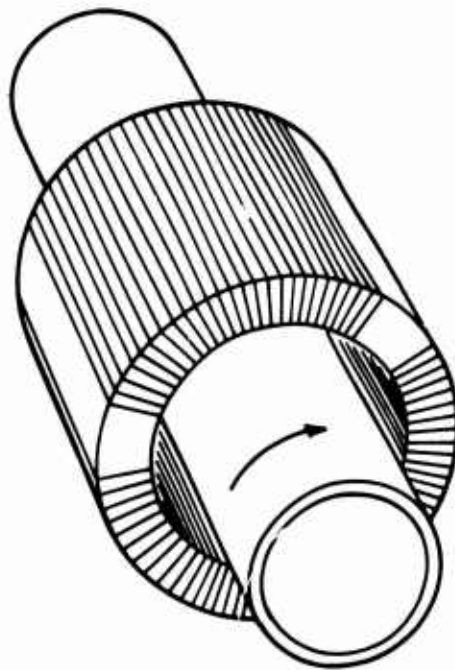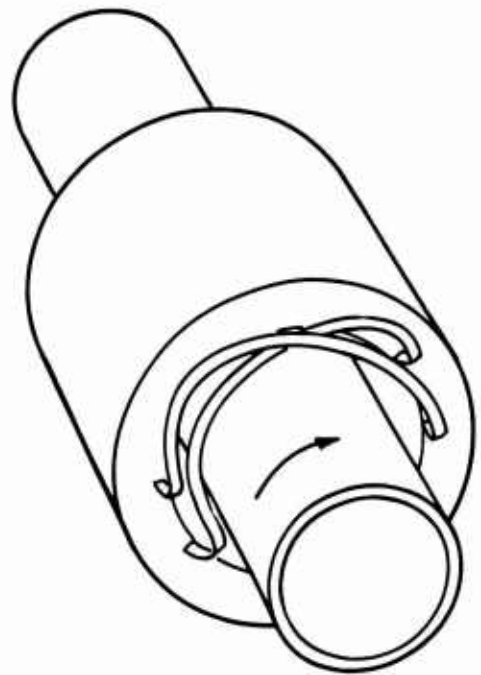
Toroidal Winding

(b)

Figure 8. Cylindrical Air-Gap Machines

losses may be virtually eliminated. A detailed study of this type of machine was conducted by the Avco-Everett Research Laboratory.

In the Avco design, the superconducting field windings are mounted inside a Dewar filled with helium and do not rotate. The hollow tubular armature rotates around the outside of the stationary field and Dewar assembly. Since the rotating member is at room temperature, the windage losses are negligible.

This form, with the armature outside, is the result of an optimization study by Avco. To evaluate the design at the 3000-horsepower level, a scaled-up version of the Avco motor was designed. The result was a motor/refrigerator design weight about twice that of the equivalent totally superconducting machine.

4.5   Cryogenic Machines

An optimization study (see Appendix IV) was undertaken to determine the possible use of cryogenic temperature copper-wound motor/generators in the electrical transmission system. The study indicated an optimum operating temperature of 40° - 50° K for minimum system weight. However, the total system weight proved to be between two and three times as heavy as a superconducting system at the same power level.

As the temperature decreases, the resistivity of the copper also decreases, permitting the use of higher current densities for constant resistive losses. The iron losses, on the other hand, increase slightly with decreasing temperature. However, the effect is small, and for this study the losses were assumed constant over the 30° and 90° K temperature range at 1.4 times their room temperature value.

The study consisted of varying three geometric parameters at several temperature levels. The geometric parameters chosen were the slot depth, core thickness, and effective length. These parameters determine the loss-weight ratio for the motor at a given power level. The combined weight of the motors and the refrigerator was then calculated for each set of geometric conditions. In this manner, the optimum configuration for each temperature level was determined. The optimum weights were then compared over the range of temperatures to determine the best temperature.

The following trends were noted during the study. At temperatures below 50° K the refrigerator specific weight became the dominant factor, while above 50° K the resistive losses were the main feature. As refrigerators improve in specific weight, the optimum temperature may shift to a lower value. Also noted was that the optimum current density is about 18,000 amperes per inch square, an order of magnitude greater than for room temperature machines.

4.6   Conclusions

For the particular application which is the subject of this study, the cylindrical air-gap, conventionally wound machine without an iron magnetic return

path has been selected for further investigation. The iron can be eliminated because the speeds are sufficiently low such that windage is no problem. The AC losses are the major loss mechanism; therefore, the conventional winding was selected to minimize the total superconductor length required.

Section 5

COMPONENT DESIGN AND EVALUATION

5.1   Superconducting Motor/Generator

The basic superconducting motor/generator design configuration is shown in Figure 9. The essential features of this design are:

(1)   The armature is wound on the stator, and the field rotates. The field is excited by a relatively low DC current. This design, therefore, minimizes the problem of brushes to the high-speed rotating shaft.

(2)   Liquid metal brushes are used in accordance with the recommendations of Reference 41.

(3)   The shaft is a long, cylindrical tube with the field on the inside. This configuration results in a high shaft stiffness with low thermal conduction loss and also gives maximum support to the field windings.

(4)   Both armature and field windings are operated in the superconducting mode. They are cooled to $10°$ K by circulating refrigerated helium gas.

(5)   The entire cold region is vacuum insulated to minimize heat leaks into the cold region. In Section 3.2 it is shown that the weight of the refrigeration unit increases rapidly as the thermal load increases and as the cold-end temperature decreases. Another consequence of this fact is that a thermal shield is provided to remove as much of the heat load at a higher, intermediate temperature as possible.

The various motor designs in the following study are characterized by two parameters: (1) the ratio of the length of the active armature region to the diameter of the field (L/D) and (2) the number of poles (P).

The operating parameters considered variable are the power rating of the unit (W_o) and the operating speed (N).

The operating voltage is assumed constant at 1000 volts RMS, and all designs are for three-phase, wye connection.

27
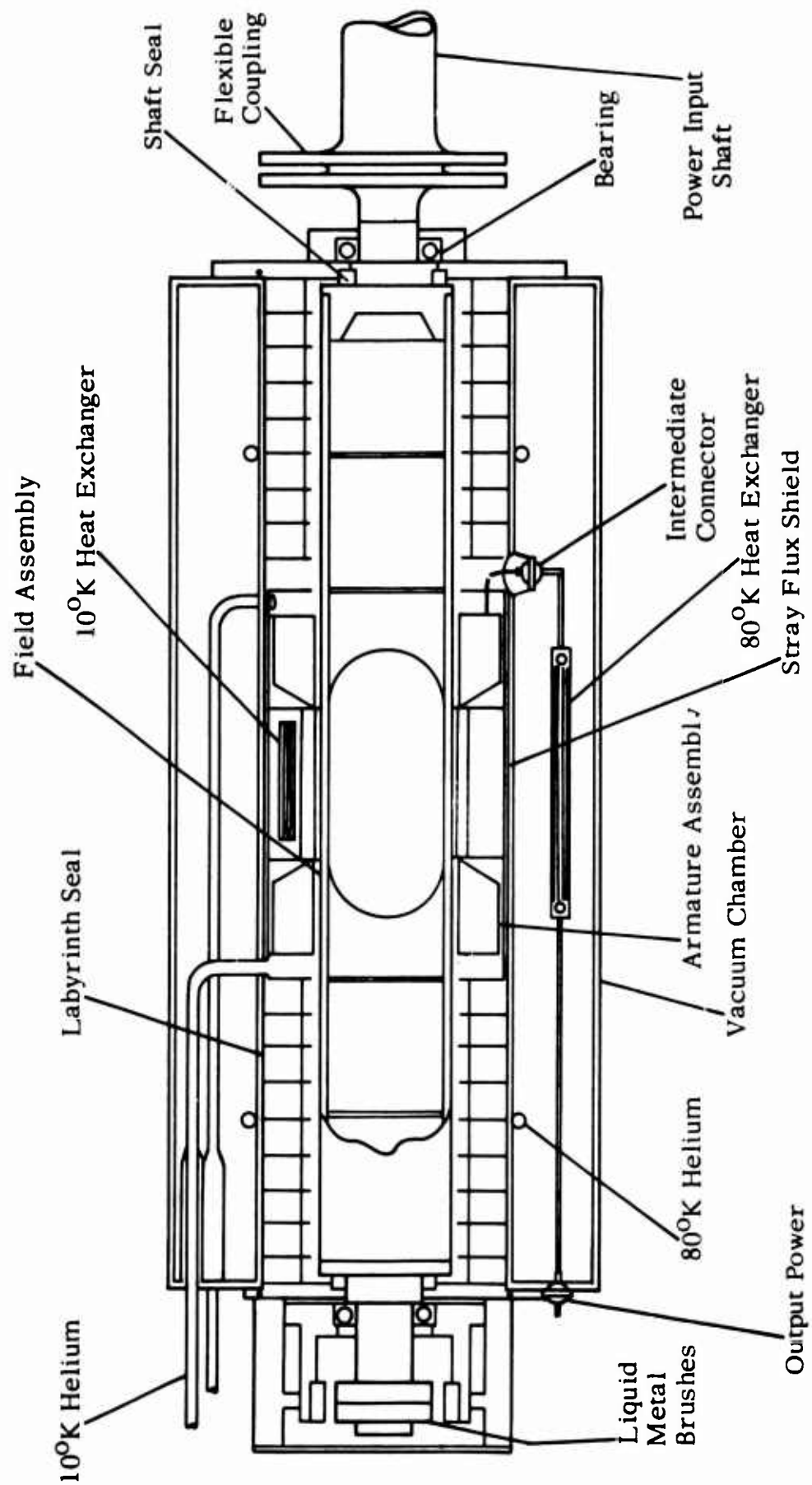
Figure 9. Basic Motor/Generator Design

A preliminary comparison of the weight and losses of three motors of different power ratings is shown in Table II and Figure 10.

Table II

Motor Weight and Losses

Rated Power (hp)	Weight (lbs/hp)	Losses (Btu/hr-hp)
250	0.200	0.660
1500	0.055	0.153
3000	0.036	0.130

It is clear that the cost of power in terms of weight and refrigeration is greatly reduced for the more powerful units. The remainder of this study concentrates on the 3000-horsepower devices.

Design Optimization

Preliminary investigation indicated that the physical and operating parameters of the superconducting motor could be selected to minimize the weight of the superconducting transmission system. The large number of interdependent variables makes it very difficult to get an explicit relation for this optimization. The most direct approach was to design a number of motors to vary the parameters separately, and to select the optimum design from plots of the design results.

A number of 3000-horsepowers motor designs were calculated (see Appendix I) for various values of speed, number of poles, and L/D ratio. A summary of the designs is given in Table III and Figure 11. It is readily apparent that an optimum (minimum) motor weight is realized at a L/D ratio between 1 and 3 while an optimum (minimum) loss occurs at a L/D ratio between 0.2 and 1.

The refrigeration system weight for an operating transmission system can be several times the weight of the superconducting devices being cooled (this point will be emphasized in greater detail in Sections 6 and 7 of this report). As a consequence, it appears reasonable to expect that the best overall system design will be optimized for the situation of minimum thermal losses.

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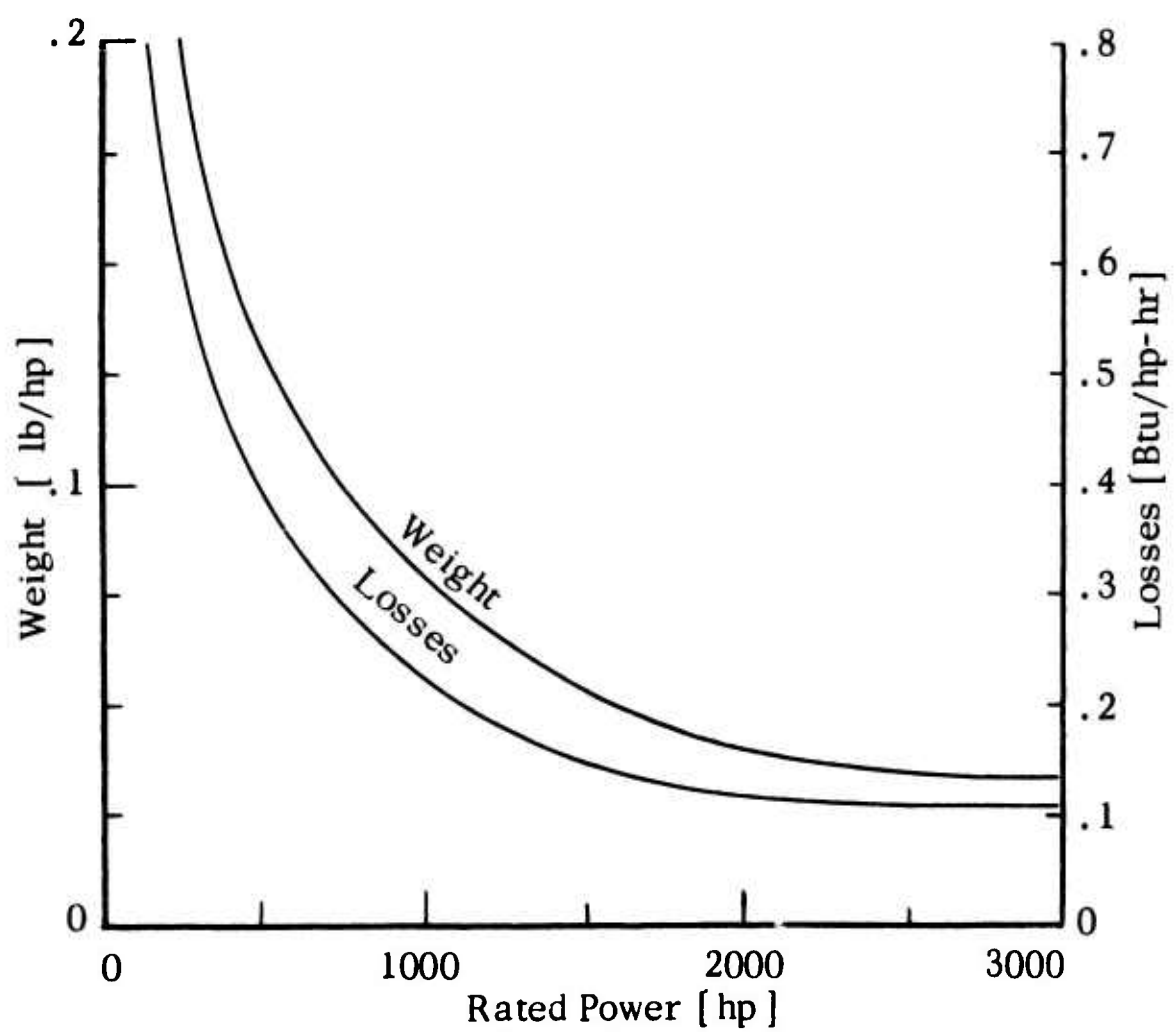
Figure 10.   Power Dependence of Motor/
Generator Weight and
Losses

Table III

Design Summary - 3000-Horsepower Motors

Design Number	Number of Poles	Speed (rpm)	L/D	W_M (lbs)	R* (Btu/hr)
1	2	12,000	18.1	122	572
2			2.6	93	452
3			0.9	98	442
4			0.4	112	515
5		6,000	36.2	194	559
6			5.1	122	421
7			2.0	119	369
8			0.9	128	348
9		1,200	18.1	772	554
10			25.5	361	412
11			9.4	287	352
12			4.3	262	314
13			2.0	267	284
14	4	12,000	14.6	119	953
15			2.5	92	728
16			0.7	96	640
17			0.3	113	700
18			0.1	136	926
19		6,000	29.2	187	938
20			5.1	122	698
21			1.4	114	566
22			0.6	125	513
23			0.3	146	482
24		1,200	14.6	732	932
25			25.4	359	689
26			7.1	252	549
27			2.9	226	476
28			1.5	230	422

Table III (continued)

Design Number	Number of Poles	Speed (rpm)	L/D	W_M (lbs)	R* (Btu/hr)
29	10	12,000	26.9	175	2131
30			3.0	97	1512
31			0.8	97	1286
32			0.3	112	1184
33			0.1	135	1354
34		6,000	53.8	299	2106
35			6.0	132	148(
36			1.5	115	1210
37			0.5	124	1010
38			0.3	146	930
39		1,200	26.9	1293	2095
40			29.9	409	1470
41			7.5	261	1193
42			2.7	221	962
43			1.4	228	850
44	20	12,000	6.1	132	2944
45			1.2	107	2317
46			0.4	117	2029
47			0.2	136	2016
48		6,000	12.1	201	2893
49			2.3	134	2231
50			0.8	134	1847
51			0.3	148	1589
52		1,200	60.6	755	2876
53			11.6	353	2210
54			3.9	268	1795
55			1.6	239	1509

* Note: When using superconducting transmission lines in conjunction with these motor designs, the losses associated with bringing the normal conducting leads out to room temperature are eliminated. (The losses associated with superconducting transmission lines are determined in Section 5.4 of this report). The tabulated losses for the motor designs should be reduced by 96 Btu/hr when using superconducting transmission lines.

Design Rating 3000 Horsepower
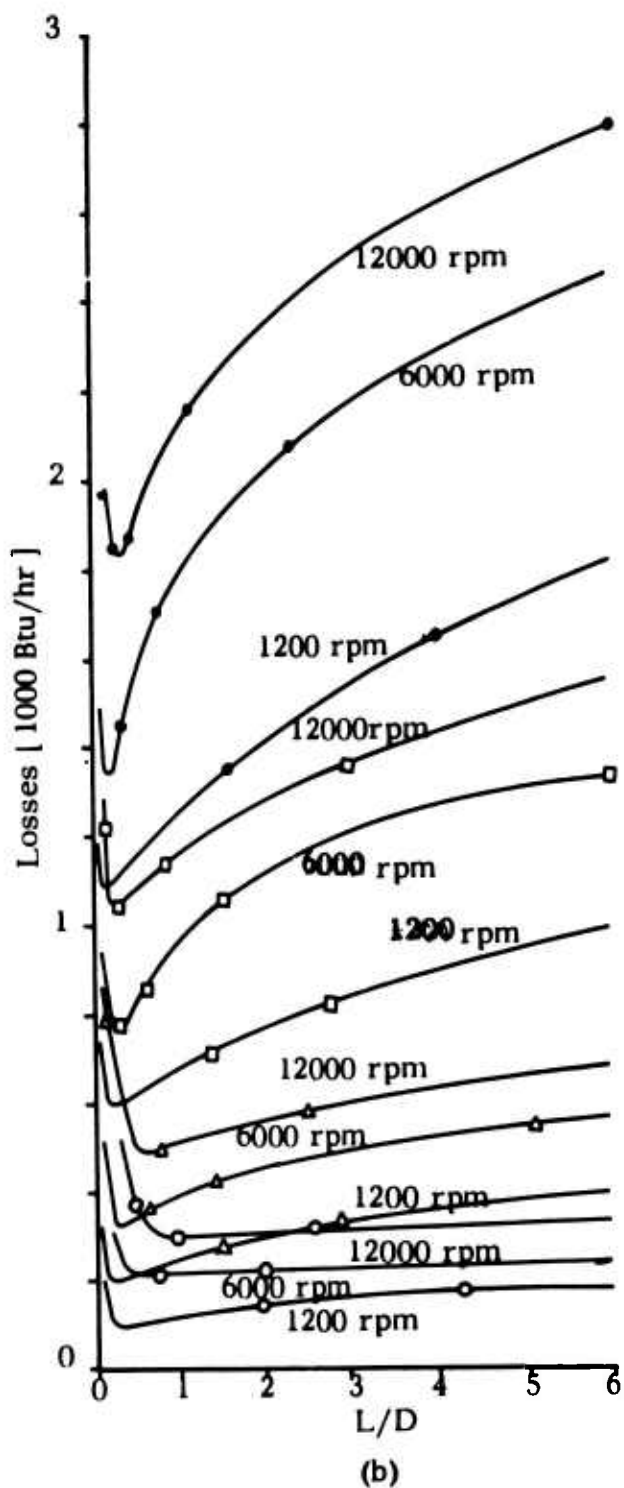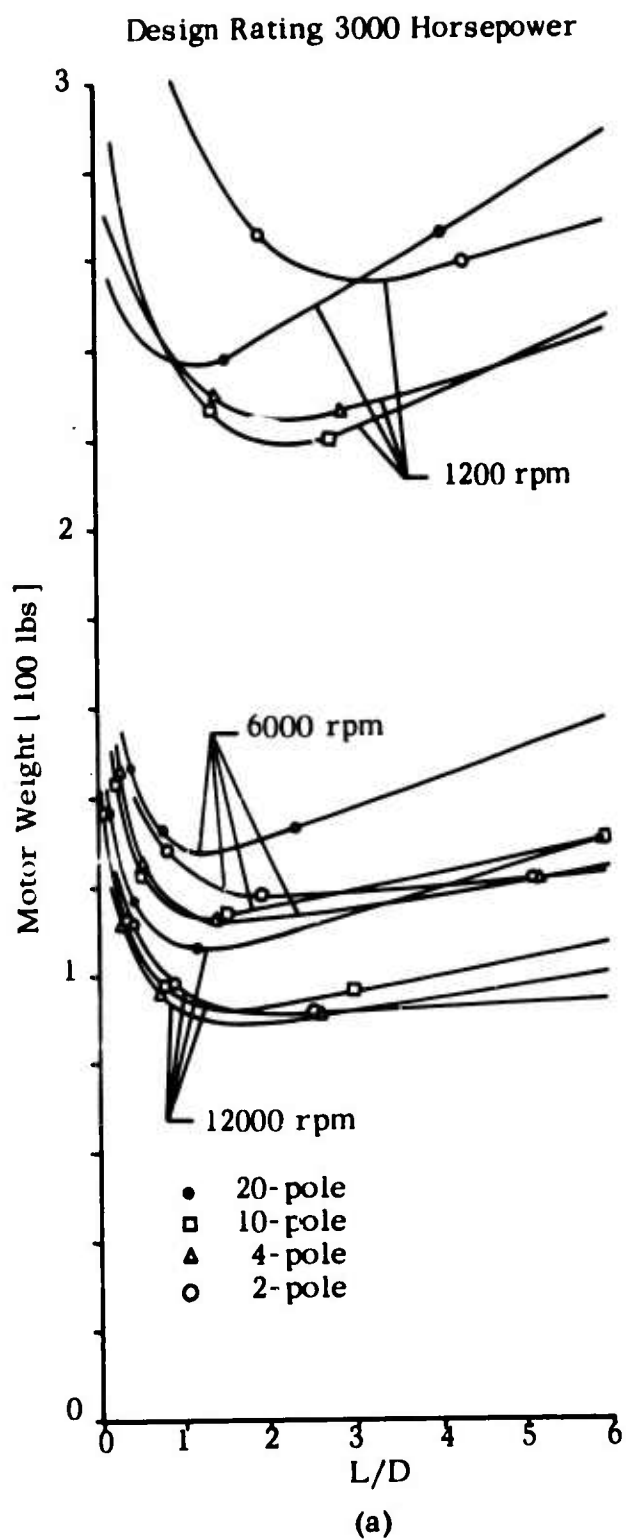
Figure 11. Design Dependence of Motor/Generator
Weight and Losses

5.2   Cryogenic Refrigeration

A necessary condition for the operation of superconductors is that the temperature be maintained below the critical temperature of the superconductor. For the materials presently avaialable and considered applicable to this study, this temperature is typically in the 10° K to 15° K region.

The heat load to the refrigerator is composed of three major factors: (1) heat losses occurring by communication with the environment, primarily by conduction and radiation, (2) heat generated in the cold region due to windage, and (3) heat generated in the cold region as a result of the rotating magnetic field and the alternating current in the armature. As the weight of the refrigeration system will be a substantial portion of the total system weight, it is desirable to reduce these losses to a minimum. Where the losses cannot be reduced, it is desirable to remove them at the highest possible temperature.

A number of thermodynamic cycles have been developed to refrigerate at cryogenic temperatures. See Section 3.2 for a complete investigation and evaluation of these various techniques. As presented in Section 3.2, the "Expansion Engine" cycle using two turbo-expanders to provide refrigeration at two temperatures and a turbo-compressor appears to be the most suitable system for this application. Figure 12 is a schematic diagram of such a refrigeration system. Figures 13 and 14 show the performance and the weight, respectively, of such a refrigeration system operating at a cold-end temperature of 10° K. The data for Figures 13 and 14 were taken from Figures 5 and 6 of Section 3.2.

The optimization of a refrigeration system would involve many parameters, and a complete optimization requires not only considerable work but a more detailed knowledge of the various system requirements and performance and weight trade-offs. To study all the parameters thoroughly would require a computer.

In comparing a refrigerator design with existing helium refrigerators, three factors must be taken into account:

(1) The helium is not liquified in this refrigerator.

(2) The heat loads in this application are much higher than those of most presently available refrigerators.

(3) The refrigerator has been designed specifically for light weight.

From the Carnot performance considerations, it is readily apparent that the work per unit heat load is considerably reduced by operating at 10° K rather than at the helium liquifaction temperature. This also results in lower refrigerator weight per unit heat load, and is the basis for deciding to remove as much of the loss heat at the higher intermediate temperature as possible.
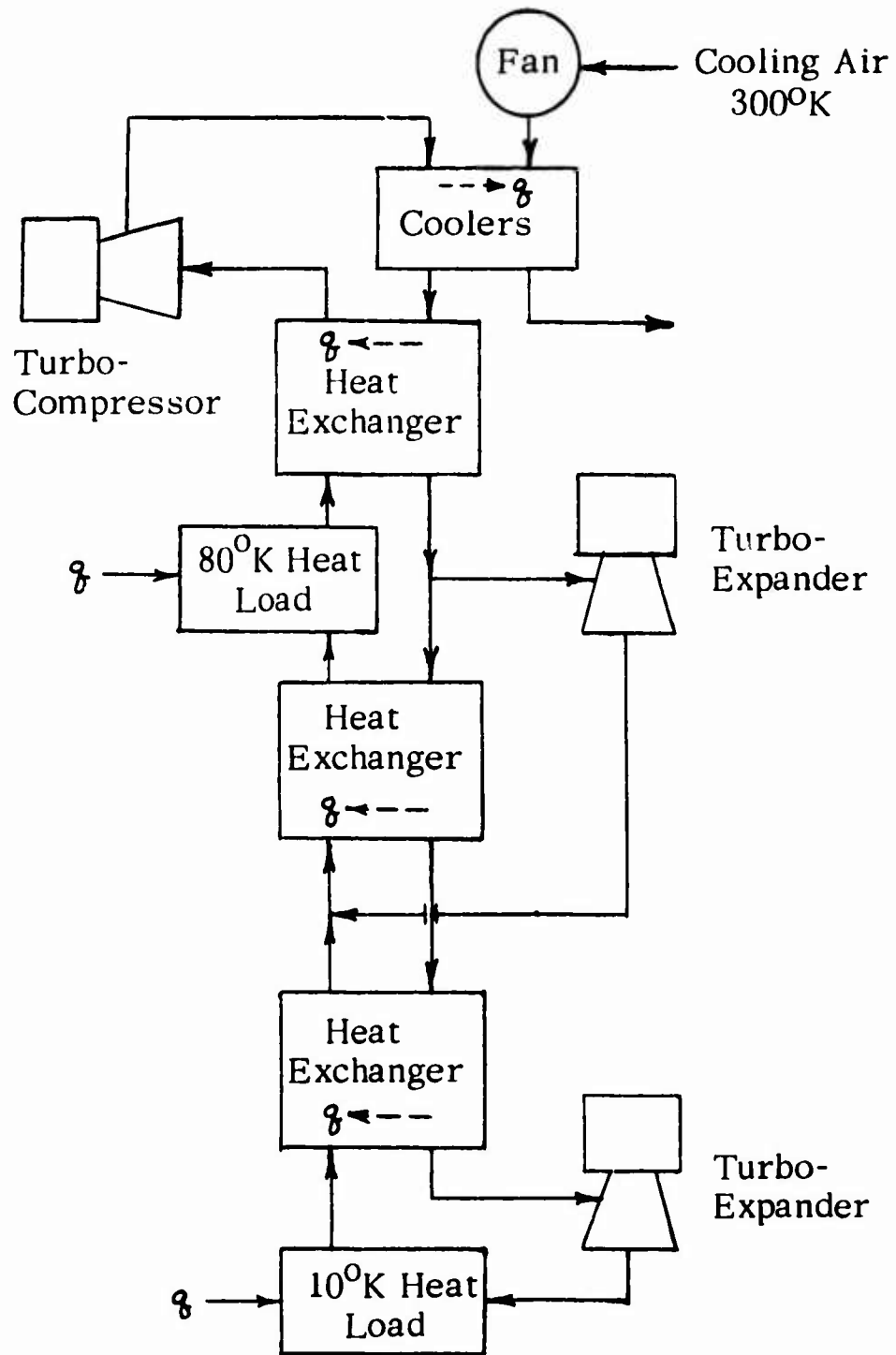
Figure 12. Refrigeration System Schematic
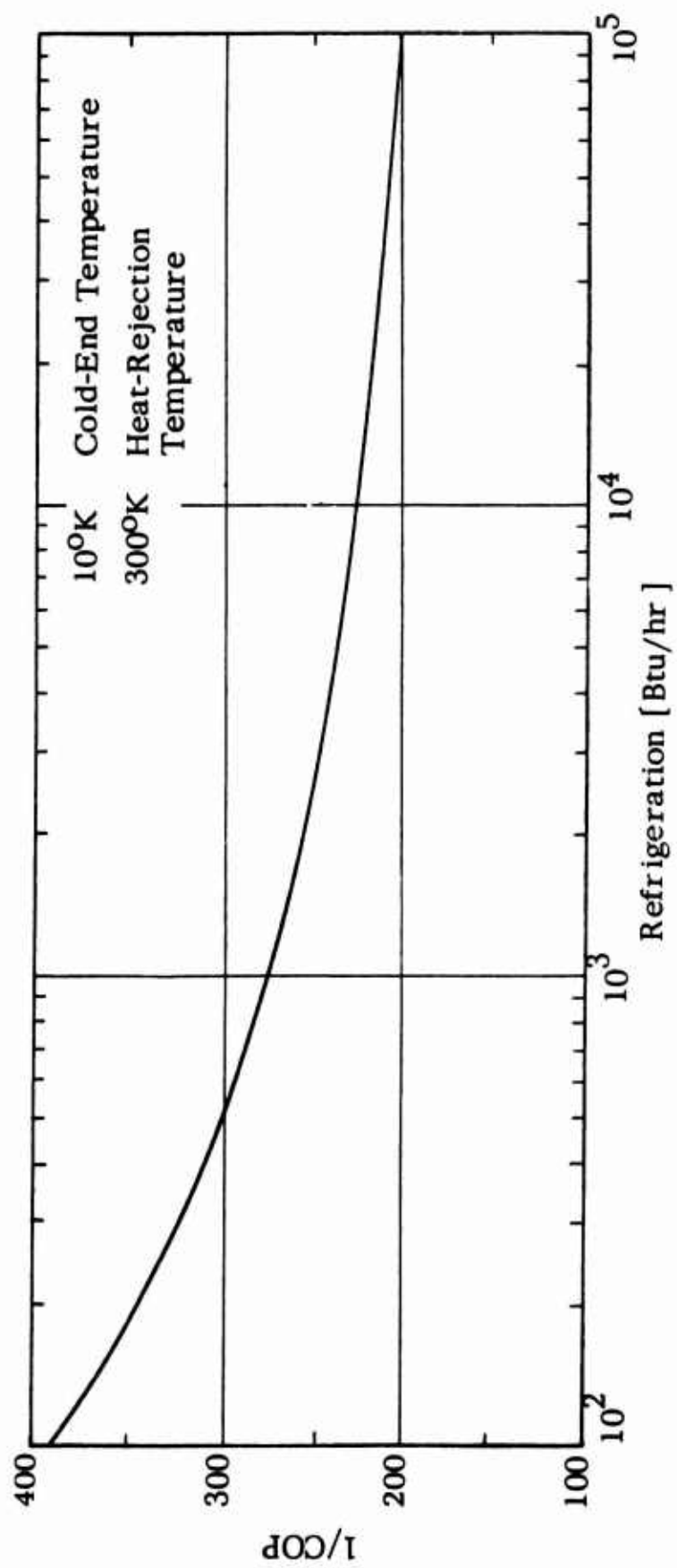
Figure 13. Refrigeration System Performance
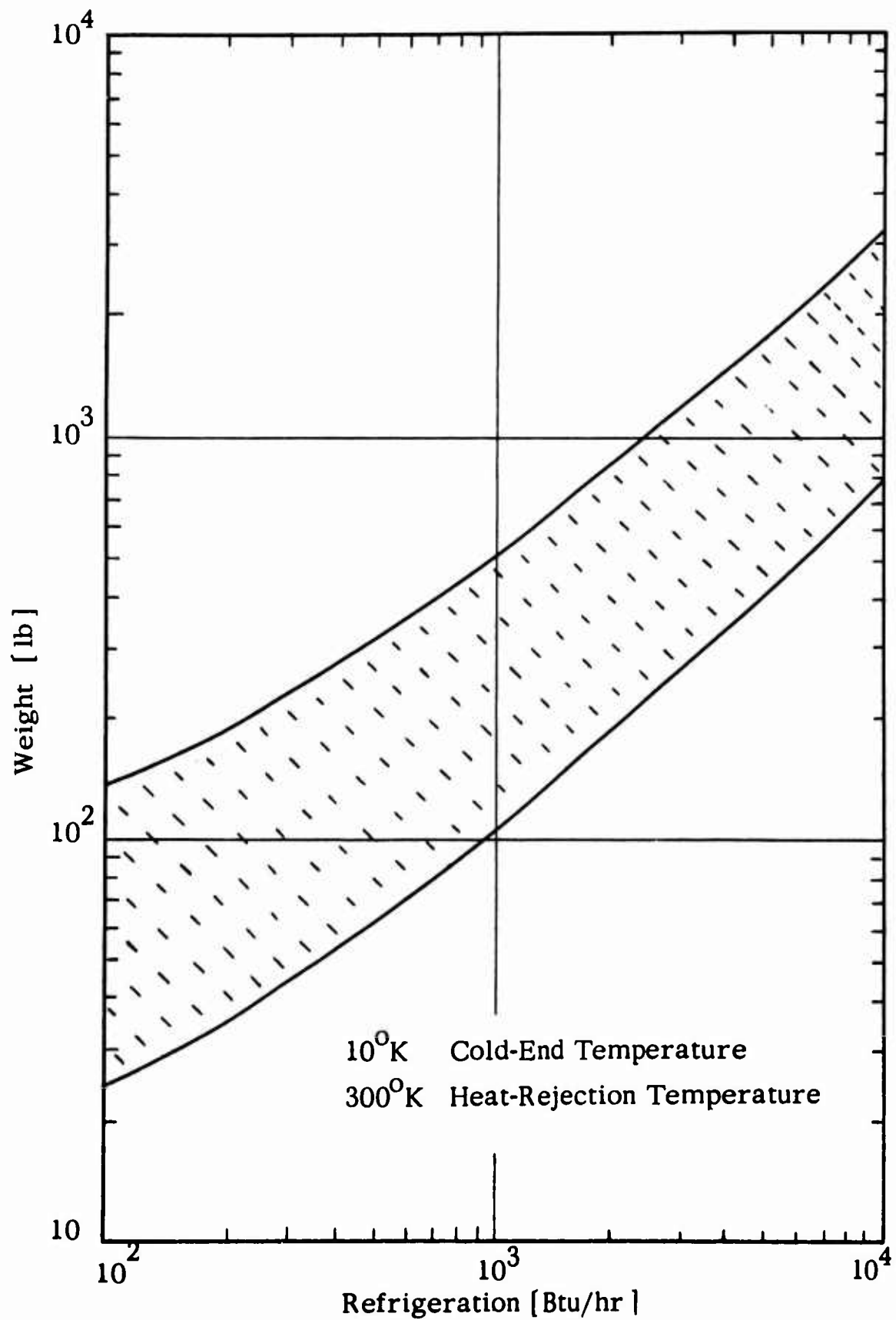
Figure 14. Cryogenic Refrigerator Weight

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5.3   Speed Reduction

A major problem which any proposed power transmission for an aircraft must solve is the problem of taking shaft power from a high-speed gas turbine and reducing it to the appropriate propeller speed. Considering mechanical and electromechanical solutions to this problem, the following methods present themselves:

(1)   Two-pole AC generators driving n-pole motors where n/2 becomes the speed-reduction ratio.

(2)   DC generators and motors designed for a desired torque/speed relationship.

(3)   AC motors and generators coupled with frequency conversion equipment.

(4)   Mechanical speed reducers.

(5)   Any combination of the above.

From the above list it is possible to eliminate solutions 2 and 3 for the present study.

Electrical machinery using superconductors can not presently be made to work beneficially in DC applications. The reason is that commutators are used, with the inherent making and breaking of electrical circuits. These interruptions give rise to surges which cause the superconductors to "quench" or "go normal". While superconductors may someday be developed which will resist "going normal" in the presence of these surges, we have not included DC components as a possible solution in this study.

Studies of AC electric drives have been conducted by the United States Army Engineer Research and Development Laboratories at Fort Belvoir, Virginia (43). The use of solid-state cyclo-converters with AC motors and generators has been shown to have attractive advantages in size, weight, and control features. Additional weight reductions can be predicted when superconducting motors and generators are employed. However, the weight of the frequency converter will be limited by improvements in cooling techniques of the solid-state devices used. The present weight of a cyclo-converter for electrical speed reduction in a high-power aircraft application is prohibitive.

Solution 1 has some promise in spite of the fact that the high-power motor running at propeller speed becomes rather large and less efficient. This increase in weight is somewhat offset by the elimination of mechanical speed reducers, which are themselves rather large and heavy.

For a system composed of motors and generators in an electrical drive, a system employing a 2-to-1 mechanical speed reducer between the turbine

and the generator (where the speeds are high and the torque and weight correspondingly low) followed by a 5-to-1 electrical spe d reduction (2-pole generators driving 10-pole motors) appears very attractive.

5.4 Superconducting Transmission Lines

The special problems associated with the design of an efficient superconducting transmission line are:

(1) The high ratio of surface area to volume necessitates an extremely low heat transfer coefficient from the cryogenic region to the environment.

(2) The cryogenic line and insulation should be electrically non-conducting to eliminate eddy current losses which would place an added load on the refrigeration capacity.

Both of these requirements are met by a recently developed plastic laminate which has vacuum retention qualities at liquid helium temperatures. The transmission line would be constructed as a double , concentric walled tube of this plastic with the superconducting line and cryogenic helium in the center tube and a vacuum in the annulus between the two tubes. A separate line would be provided for each phase to eliminate interaction and to minimize the hysteresis losses in the superconductors.

Use of the superconducting transmission lines eliminates the necessity of bringing normal conducting leads into the superconducting region of the motors and generators. This eliminates the requirement for lead heat exchangers and reduces the refrigeration load for each machine by a considerable factor.

The transmission lines perform a double function. In addition to the current carrying function, they also act as the refrigerant lines. The size of the line is determined by the helium refrigerant flow rate, which in turn is determined by the total refrigerating load for the cooling circuit being considered.

Figures 15 and 16 show the approximate weight and volume and the losses of the superconducting transmission line as a function of the total refrigeration load for the cooling circuit and the total power conducted through the transmission line.

The vacuum in the annulus between the two tubes, while perhaps initially evacuated by mechanical pumping, will be maintained during operation by the cryo-pumping associated with the helium refrigerant line in the center.
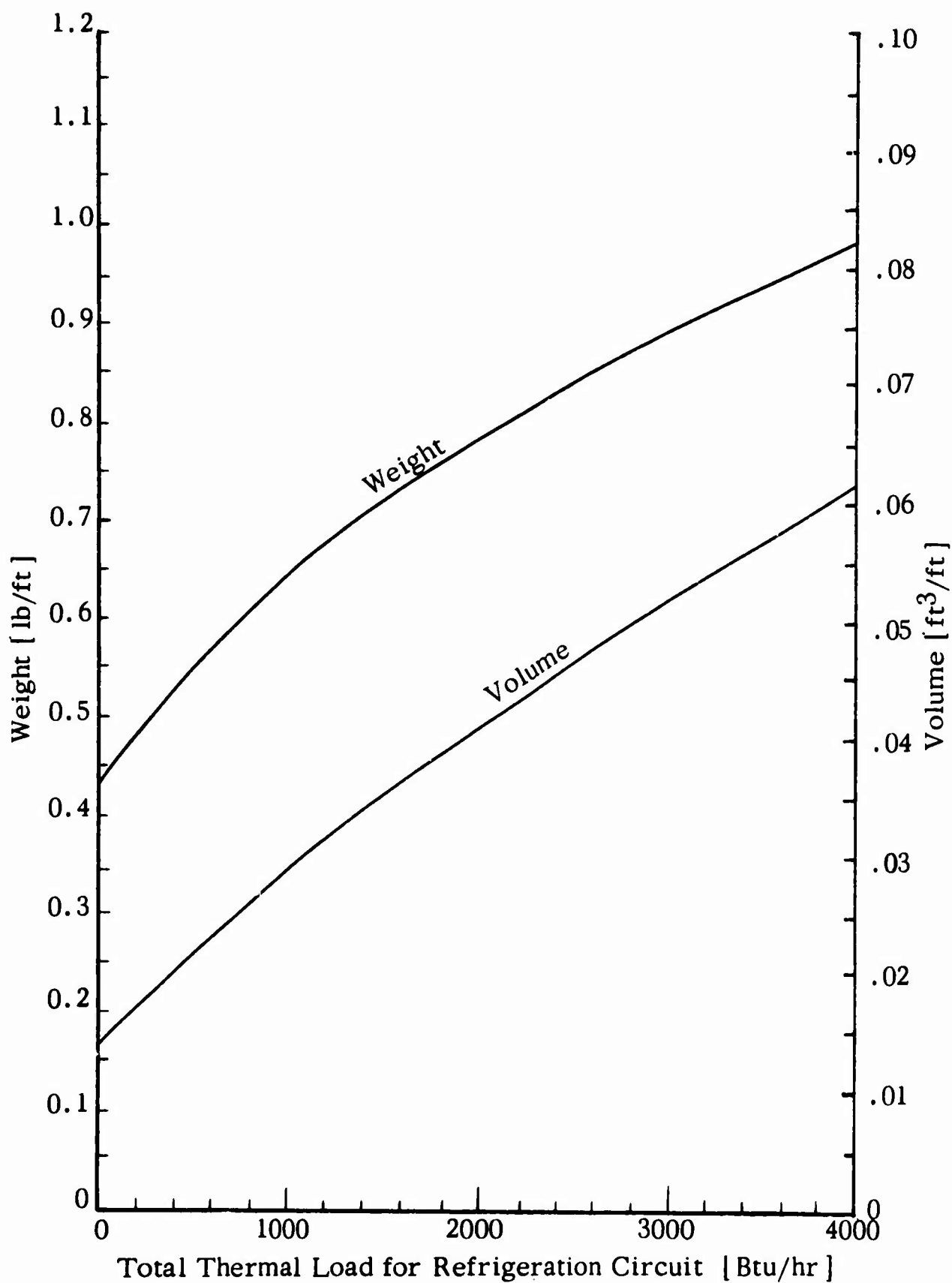
Figure 15. Transmission Line Weight and Volume

40
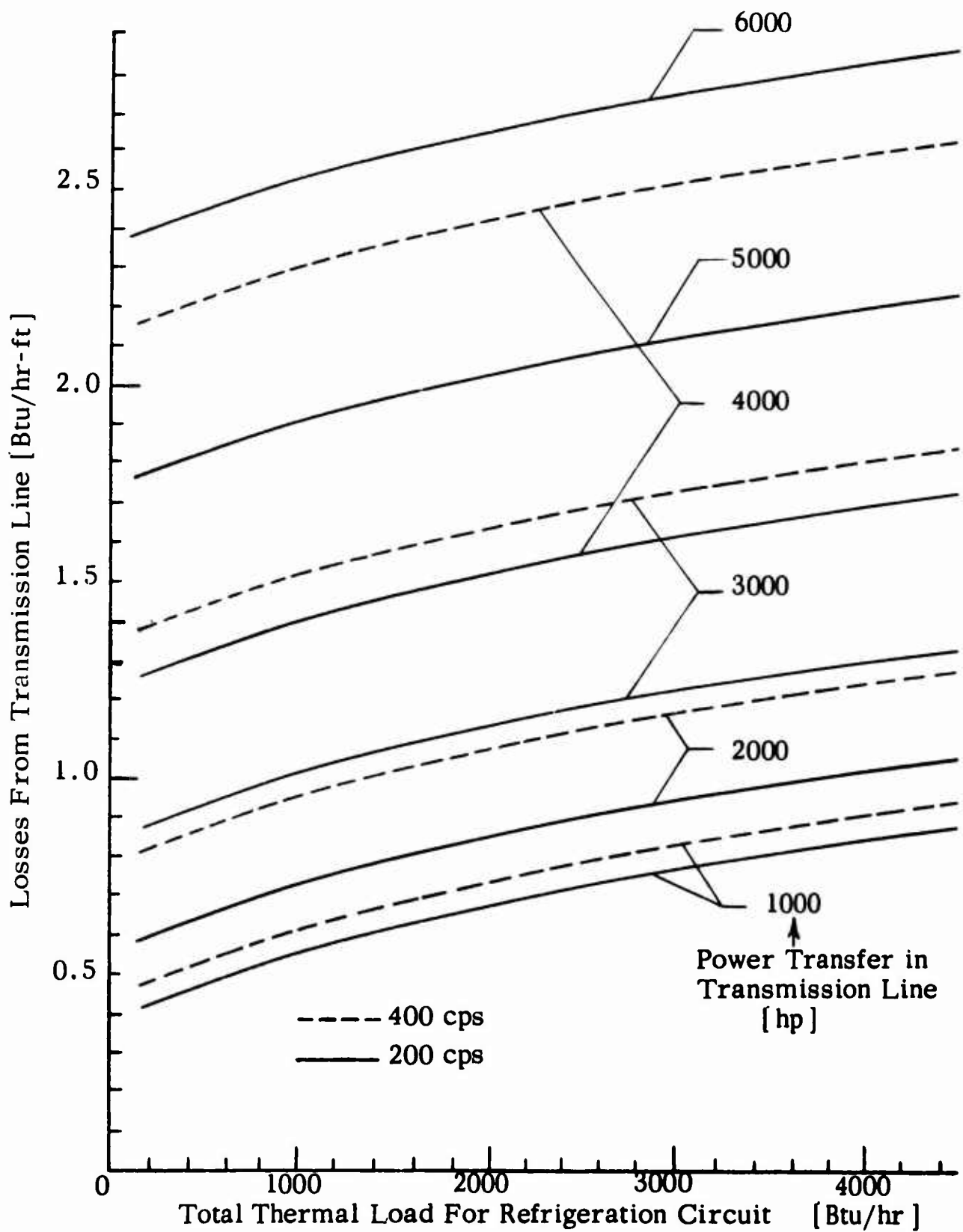
Figure 16. Transmission Line Losses

Section 6

SYSTEM DESIGN AND EVALUATION

6.1   Sxstem Design

For the purpose of determining the best electrical transmission
system design, five basic configurations, each approximating the general
specifications of the XC 142A V/STOL aircraft, were considered.

System A (Fig. 17a) is a straightforward electrical system which
uses four 2-pole generators driving four 2-pole motors (one for each pro-
peller), mechanical speed reduction to drop the motor speed to the propeller
speed, and a single refrigeration unit servicing all superconducting devices.

System B (Fig. 17b) is similar to System A with the exception
that four 20-pole motors replace the 2-pole motors and mechanical speed re-
ducers, and the 10-to-1 reduction is accomplished by virtue of the relation
of the speed of the 20-pole motor to the frequency of the power generated by
the 2-pole generator.

System C (Fig. 17c) combines features of Systems A and B where-
by 10-pole motors are driven at prop speed by 2-pole generators driven at
half the turbine speed through a 2-to-1 mechanical speed reducer.

System D (Fig. 17d) uses the superconducting system for cross-
coupling only. A straight-through shaft between each turbine and its related
propeller provides the primary power transmission. Speed reduction is
accomplished mechanically.

System E (Fig. 17e) uses four 2-pole generators operating at
turbine speed to generate electrical power at 200 cycles per second. A solid-
state frequency converter reduces the frequency to 20 cycles per second.
The low frequency power drives four 2-pole motors at propeller speed.

To enable a comparison of the major system differences to be made
on a common basis, the following assumptions are made:

(1)   The total output power of each system is 12,000 horse-
       power (3000 horsepower from each device).

(2)   All systems use superconducting transmission lines.

(3)   The length of transmission line between each motor
       and generator pair is 10 feet. The length of cross-
       coupling transmission line is 40 feet.

(4)   The normal cross-coupled power is 10 percent of the rating
       of each device, or 300 horsepower.

(c) Composite System

(b) Electric Speed Reduction

(a) Electrical Drive System

(e) Cyclo-Converter System

(d) Electrical Coupling Only

∞ — Propeller
◇ — Speed Reducer
Ⓜ — Motor
⌁ — Cyclo-Converter
Ⓖ — Generator
◁ — Turbine
□ — Refrigerator
═ — Mechanical Coupling
— Electrical Lines
--- — Refrigerant Lines
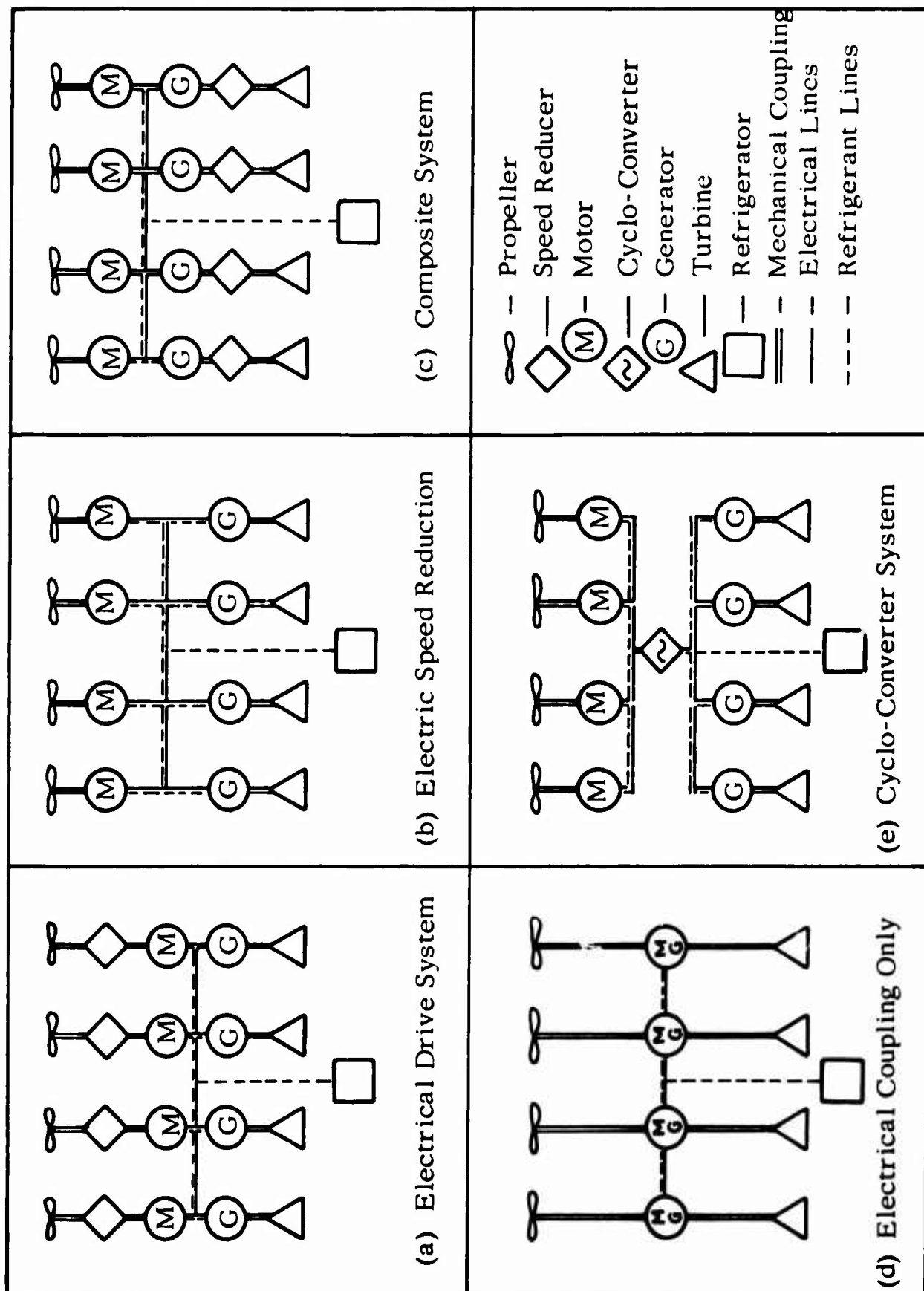
Figure 17. Electrical System Design Schematics

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(5)   Each system is optimized on the basis of minimum
        total system weight by varying the L/D ratio.

The comparative results of the five electrical system designs are summarized in Table IV. It should be noted that assumption (1) on the previous page actually imposes a penalty on System D, electrical cross-coupling only, because with this system the maximum power that any motor/generator will be required to supply will be three-fourths of the engine power, or 2250 horsepower.

The extreme dependence of system weight on the weight of the refrigeration unit is brought out by comparison of the upper and lower weight, estimates for the various systems. System B, which has a large refrigeration load, appears as an unattractive selection on the basis of the higher refrigeration weight, but is one of the best systems on the basis of the lower refrigeration weight.

System D is consistently the lightest arrangement. The reason is obvious when it is considered that the motor and transmission line are replaced by a simple shaft which has no refrigeration requirement. This system has other advantages, such as safety, but this will be discussed later in comparison with the mechanical transmission system.

System E is overweight by a factor of 3 or more. It will not be considered further.

Based upon the preliminary design comparison in Table IV, system B (Electrical Speed Reduction) and system D (Electrical Cross-Couple Only) were selected for more complete development and for final comparison with the mechanical system in Section 7.

6.2   System Control

Parallel Operation

For simplicity, the first part of this description will assume only two identical machines to be in operation. Appendix II gives the mathematical basis for the following description.

If we consider two identically wound superconducting synchronous machines in parallel, and assume constant synchronous reactance, neglecting all resistance effects, then we have the following well-known effects:

(1)   If they are moving as alternators separately at the
        same speed with no phase angle (or "load angle")
        between their emfs, and are identically excited,
        then there is no voltage difference between their
        terminals. They may be paralleled, and, unless
        the excitation is changed or the speed of one prime
        mover starts to change, then they will remain in
        equilibrium with no current circulating between them.
        This condition   (of no circulating current) will not be

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Table IV

Preliminary Design Summary
Electrical Transmission Systems

		Weight lb	Losses Btu/hr
(A)	**Electrical Transmission System**		
	- generators, 2-pole, 12,000 rpm	412	1200
	- motors, 2-pole, 12,000 rpm	412	1200
	- motor coupling	18	120
	- mechanical speed reducer 10:1	1652	---
	- cross-coupling	18	60
	- refrigerator	230/1030	---
	Total	2742/3542	2580
(B)	**Electrical Speed Reduction**		
	- generators, 2-pole, 12,000 rpm	412	1200
	- motors, 20-pole, 1200 rpm	1380	4560
	- motor coupling	24	137
	- cross-coupling	24	77
	- refrigerator	490/2100	---
	Total	2330/3940	5974
(C)	**Combination Speed Reduction**		
	- generator, 2-pole, 6000 rpm	560	840
	- motor, 10-pole, 1200 rpm	1160	2400
	- motor coupling	18	89
	- mechanical speed reducer 2:1	200	---
	- cross-coupling	18	59
	- refrigerator	295/1300	---
	Total	2251/3256	3388
(D)	**Electrical Cross-Couple Only**		
	- generator/motor, 2-pole, 12,000 rpm	412	1200
	- mechanical speed reducer 10:1	1652	---
	- cross-coupling	14	46
	- refrigerator	123/590	---
	Total	2201/2668	1246

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Table IV (Continued)

	Weight (lb)	Losses Btu/hr
(E) Frequency Converter System		
- generator, 2-pole, 12,000 rpm	412	1200
- motor, 2-pole, 1200 rpm	1200	480
- frequency converter	5000	---
- motor coupling	17	84
- cross-coupling	17	36
- refrigerator	170/780	---
Total	6816/7426	1800

affected if a "load" is placed on the two machines (either in the form of an electric load at the terminal or in the for.n of dynamometer loads if they now operate as motors from an external electrical supply). They are equally sharing the load.

(2) If the excitation is unchanged but one prime mover starts to speed up, then there is a voltage difference between the two machines, which for small "load angles" is almost in quadrature with the terminal voltage. This causes a circulating current (lagging the voltage difference by 90°) to occur. This current is essentially in phase with the "fastest" machine voltage and in antiphase with that of the "slower" machine. This current therefore represents load on the faster machine (which tends to slow or reverse its acceleration, and is therefore a stabilizing influence for small load angles); this tends to supply power to the slower machine, causing it to motor and hence aid in its acceleration so that the two machines remain in step. Note that if the "governor characteristics" of the two machines are not identical, there will be uneven loading on the two machines, giving a tendency for one to generate and the other to motor at or near no-load condition.

(3) Changing the excitation of two synchronous generators operating in parallel will not affect the load sharing, but will merely cause zero power factor circulating currents. Thus it is most important not to alter excitation of parallel generators or motors. It will probably be best either to have the excitation external to any control or, if it is necessary to reduce excitation (as suggested later), to operate the circuits in series with one another. This is not usually a wise procedure unless characteristics are so nearly identical as to be almost unbelievable.

Bearing in mind the above results, we see that the system will tend to be stable for reasonable perturbations and that it will be possible to share loads in a reasonable manner. The next question to be considered is therefore that of startup.

Startup

It is rather surprising to find that according to the simple theory of AppendixII, the short-circuit current is independent of speed. This is because both the emf and the synchronous impedance are linearly dependent on speed, and hence the ratio of the two is essentially independent of speed. In normal machines, the resistance and secondary saturation effects tend to change this, but for a non-resistance machine, these effects will be absent. It can be assumed that a synchronous impedance of about 100 percent would be chosen to give suitable short-circuit

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protection. However, this could have one serious disadvantage as far as the startup is concerned, in the condition where one machine is to be used to accelerate all the others.

The results of Appendix II show the following interesting facts:

(1) The current on parallel operation is independent of the speed (in the same way as for short-circuit current).

(2) The torque is independent of speed; it is mainly a function of the flux and current, which is tantamount to saying the square of the flux.

If we could work with higher flux, we could achieve higher torque (with greater currents), but this would probably not be possible, since it is assumed that we are normally operating with as high a field as is reasonable within the critical current limit. Therefore, it seems that, provided there is no need to start up all the motors from one machine, or provided it is possible to shed load (by feathering the props) during startup, there is no problem. However, if it was ever necessary to run, say, three machines acting as motors from one acting as a generator, then there must be additional controls to ensure an equable load current and torque reduction; under these circumstances it may be necessary to reduce the flux of all machines so that the maximum current drawn is within the rating of the drive machine (see also notes in Appendix II).

6.3   Failure Modes

The modes of failure that are peculiar to the superconducting system are those that cause the loss of the superconducting state. In this sense there are only two states: superconducting and not superconducting. There is no in-between state. The effect that this has on the integrity of such a system for V/STOL aircraft use depends upon the particular system configuration selected.

Specific difficulties which can lead to loss of superconductivity are:

(1) Failure of the refrigeration unit
(2) Leaks in the helium refrigerant lines
(3) Increase of environmental heat leak by loss of vacuum insulation
(4) Increase of current loss by overloading the system
(5) Short circuits

Failure of the refrigeration unit can be the result of mechanical failures, or it can result from the contamination of the helium. Particles in the refrigerant lines can cause physical damage or can block narrow passages in the heat exchangers. Any gaseous contaminants would freeze out and cause similar damage.

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Leaks in the helium or vacuum lines could be the result of normal operation or could be caused by battle damage. It is difficult to discuss such problems quantitatively; but on a qualitative basis, leaks in the system would result in a more or less gradual reduction in the net refrigeration capacity available to maintain the operating system. Extra makeup helium could be carried to prolong the useful operation in the event of a helium leak. There is a possibility that strategically placed valves and disconnects could be used to seal off damaged areas to maintain partial system operation.

Problems of overloading are basically problems of designing the system with a sufficient margin of safety.

Short circuits would also be a problem of reliability and design. Because of the nature of the superconductor, shorts would probably shut down the entire system immediately.

The effect that the failure of the superconducting machinery has upon the operation of the entire system depends upon the configuration chosen. If the completely electric or the electrical speed reduction systems are chosen, any failure will disable the plane. For the system using electrical cross-coupling only, loss of coupling will have no effect on conventional flight and may not incapacitate the craft in vertical flight if pitch and roll can be adequately controlled manually with the main propellers uncoupled. It is anticipated that roll control will be adequate and that pitch control will be possible in the STOL mode with a flight speed greater than 60 knots.

The failure modes described above are all unique to the superconducting system. There are other problems, such as loss of power in one or more engines or sudden changes in load, which affect any transmission system used. The problem is essentially one of control. In this respect, the superconducting system, which utilizes the same control devices as the mechanical system, is equivalent to a pure mechanical system in that it merely transmits the power and performs no control functions. All control in such cases is provided by the turbine and propeller controls and by the pilot.

Section 7

COMPARISON OF MECHANICAL AND SUPERCONDUCTING
TRANSMISSION SYSTEMS

7.1 Description of Systems

For comparison of the proposed electrical transmission system with an equivalent mechanical system, a specific airplane, the XC-142A triservice V/STOL, was chosen. The XC-142A is a tilt-wing cargo assault aircraft presently under development. It is an all-weather troop, equipment, and supplies transport. For a more detailed description, see References 44, 45, and 46.

The mechanical power transmission system is shown schematically in Figure 18a. The shaded portions are those that are to be replaced by the electrical power transmission systems shown in Figure 18b and 18c. Basically, the eliminated items are the cross-coupling shafting with its related gearboxes, all or part of the main propeller gearcases, the pivot and accessory gearcases, and the clutch and shafting to the tail propeller.

The superconducting transmission systems can be described as electrical cross coupling only (Fig. 18b) or as electrical speed reducing (Fig. 18c). The major components of the electrical cross-coupling system are the speed-reducing portion of the propeller gearcases, four main superconducting motor/generator units, one superconducting tail power motor with a power contactor, a refrigeration unit and accessory gearcase driven by a single auxiliary power turbine, and superconducting electrical transmission lines connecting all the components.

The electrical speed-reducing system is similar to the electrical cross-coupling system with the exception that the mechanical speed reducers are replaced by 20-pole superconducting motors which are driven by the 2-pole generators, thereby reducing the speed by a factor of 10.

The electrical transmission systems proposed perform two major functions: (1) they permit cruising on two engines using all four propellers in the conventional flight mode (a more economical situation than feathering the extra props which are of a high-camber design), and (2) they provide cross coupling to distribute power for flight control in the vertical flight mode, including emergency power distribution in the event of a power failure. The operational specifications and characteristics are given in Table V.

Table V

Operational Specifications and Characteristics

Main propulsion	- four 3000-hp, 12,000-rpm turbines
Propeller speed	- 1200 rpm
Tail rotor power	- 950 hp maximum
Tail rotor speed	- 2400 rpm
Cross coupling for control	- 850 hp maximum

The rating of the main motor/generators of the electrical cross-coupling system is determined by the emergency condition of an engine failure during vertical flight. In this situation, the three remaining engines generate the power to drive the fourth propeller. With one engine out, the total system power remaining is at three-quarters of rating. Each generator/motor must therefore be rated at 2250 horsepower. The complete design specifications for the main generator/motors and for the tail motor are given in Table VI.

Table VI

Design Specifications
Electrical Cross-Coupling System

	Generator/Motor	Tail Motor
Power rating	2250 hp	950 hp
Voltage	1000 volts, 3 phase	1000 volts, 3 phase
Speed	12,000 rpm	6,000 rpm
Poles	2	4
Weight	90 lbs	95 lbs
Losses	272 Btu/hr	111 Btu/hr

For the electrical speed-reducing system, the main motors and generators must handle the full 3000-horsepower rated load. The complete design specifications are as given in Table VII. There is no change in the tail motor from that specified in Table VI.

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(a) Mechanical System

(b) Superconducting System
Cross-Coupling Only
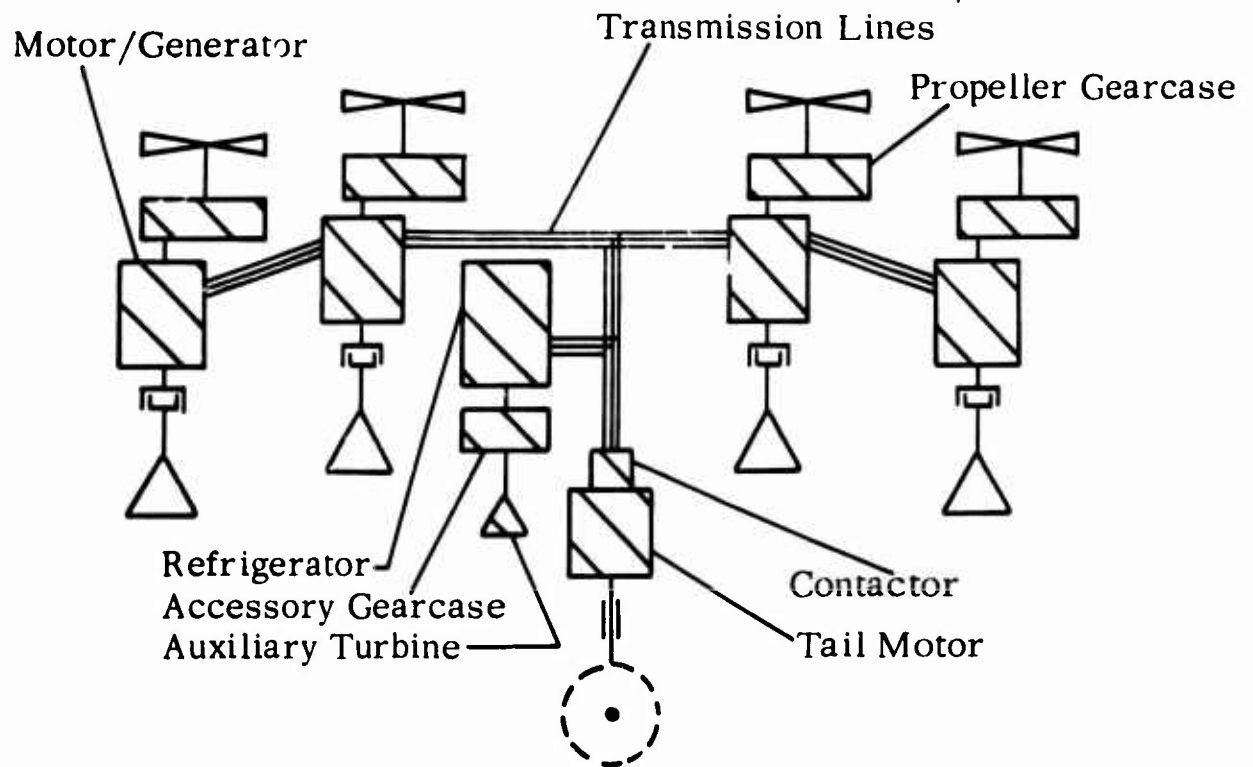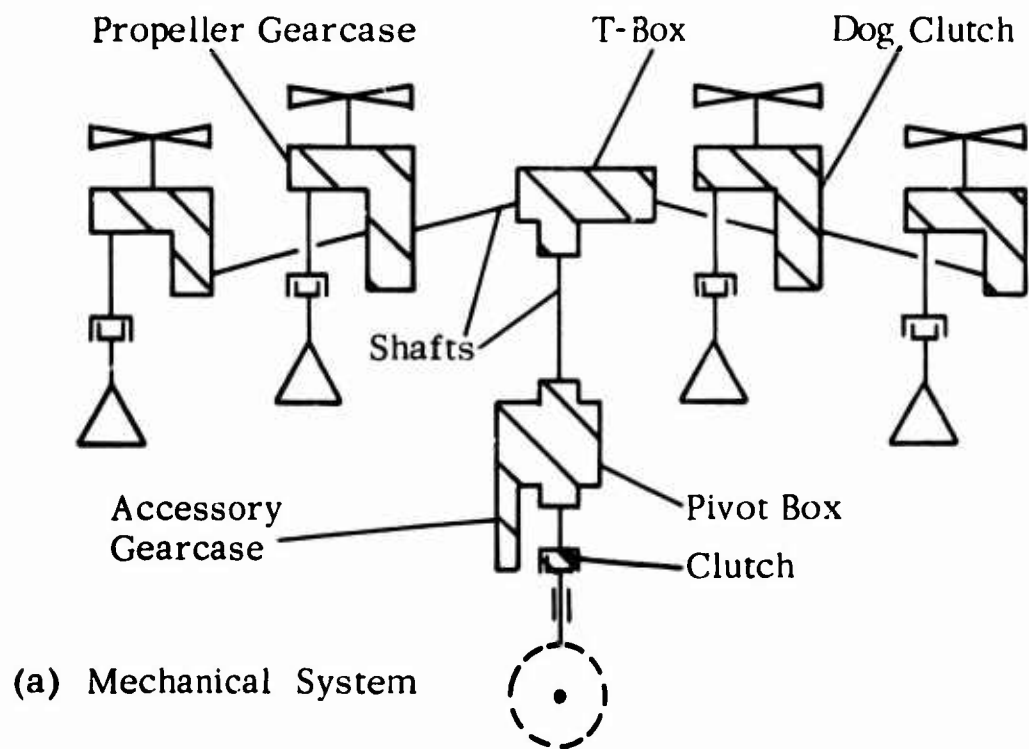
Figure 18. Transmission System Schematics

Transmission Lines

Motor

Refrigerator
Accessory Gearcase
Auxiliary Turbine

Generator
Contactor
Motor
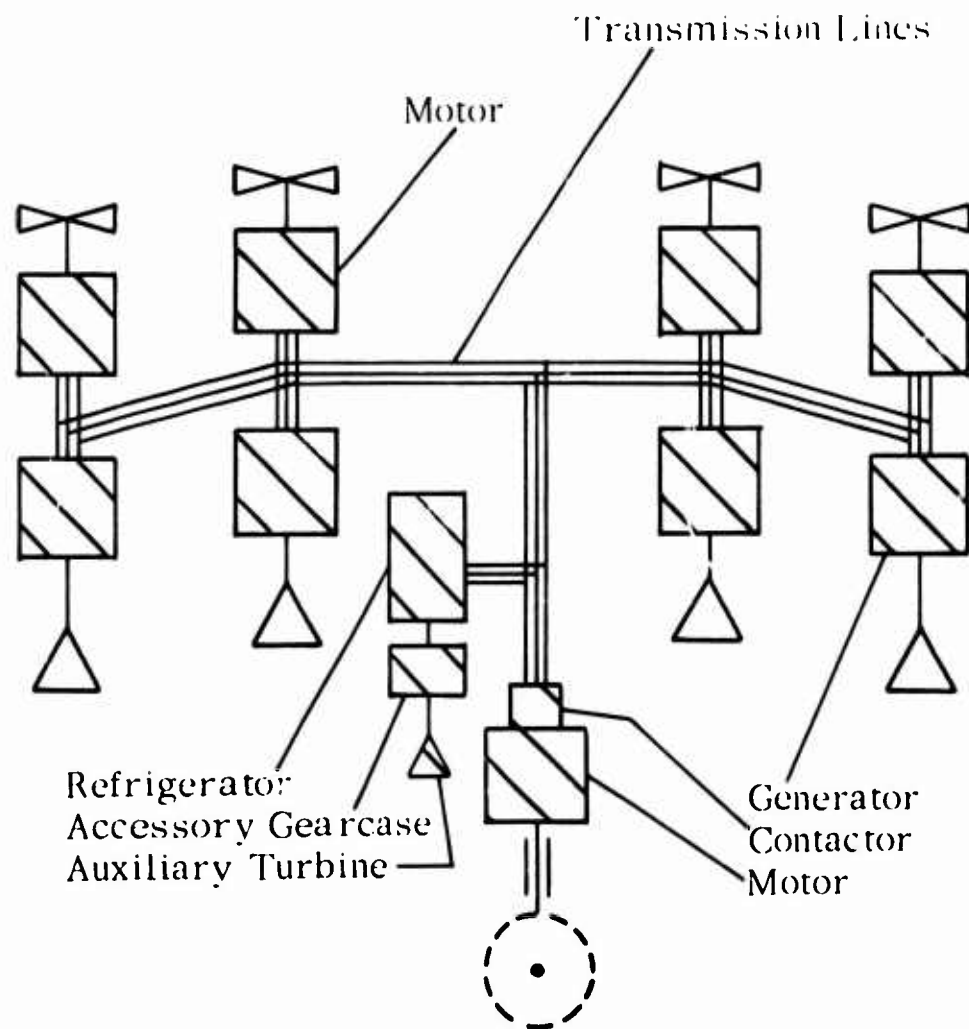
(c) Superconducting System
Electrical Speed Reduction

Figure 18 (Cont d)

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Table VII

Design Specifications
Electrical Speed-Reduction System

	Motor	Generator
Power rating	3000 hp	3000 hp
Voltage	1000 volts, 3 phase	1000 volts, 3 phase
Speed	1200 rpm	12,000 rpm
Poles	20	2
Weight	345 lbs	103 lbs
Losses	1140 But/hr	300 Btu/hr

7.2 Weight Comparison

A comparison of the estimated weight of the superconducting transmission systems specified in the preceding section and the equivalent mechanical transmission system is summarized in Table VIII.

Items which are common to all three systems are not included in the weight comparison.

By this comparison the superconducting systems appear competitive with the mechanical system. The wide range in refrigerator weights emphasizes the penalty of the electrical speed-reducing system; however, there is good reason to expect that the larger refrigeration units will benefit most from the change to turbo-machinery, thus realizing the more optimistic weight projections.

Other factors that also should be considered in a complete comparison of system weights are the weight penalties resulting from inefficiency (see Section 7.4) and from system cool-down (see Section 7.6).

7.3 Volume Comparison

Detailed information required to determine the relative volume of many of the components in the three systems considered was not available. An estimate for mechanical components was arrived at by determining approximately what proportion of the component volume is steel and what proportion is aluminum from layout drawings, calculating an average density for the entire component, and thereby determining the total volume from the known weight. The volume of refrigerator systems, where actual designs are not available, was determined by estimation of the average density, hopefully on the conservative side, and calculation of the volume from the known weights. The volumes of the superconducting devices were calculated directly from the designs. The comparative results of the volumes so determined are shown in Table IX.

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Table VIII

System Weight Comparison

Mechanical System

(Mechanical component weights supplied by
Aviation Materiel Laboratories)

- Shafts, couplings, bearing supports		289 lbs
- Main propeller gearcase		1900
- T-box		113
- Pivot and accessory gearcase		151
- Tail rotor clutch		30
	Total	2483 lbs

Electrical Cross-Coupling System

- Generator/motors		360 lbs
- Tail motor		95
- Main speed reducers		1652
- Cross-coupling lines		56
- Tail motor transmission lines		56
- Accessory gearcases		15
- Refrigeration unit including turbine		125/600 *
	Total	2359/2834 lbs

Electrical Speed-Reduction System

- Generators		412 lbs
- Main motors		1380
- Tail motors		95
- Main motor coupling lines		96
- Tail motor coupling lines		56
- Cross-coupling lines		96
- Accessory gearcase		15
- Propeller supports		330
- Refrigeration unit including turbine		495/2100 *
	Total	2975/4580

* The ranges in refrigeration unit weights are the limits of the refrigerator
designs as outlined in Figure 14.

Table IX

System Volume Comparison

Mechanical System

- Shafts, couplings, bearing supports		0.69 ft^3
- Main propeller gearcases		10.50
- T-box		0.87
- Pivot and accessory gearcase		1.16
- Tail rotor clutch		0.17
	Total	13.39 ft^3

Electrical Cross-Coupling System

- Generator/motors		5.80 ft^3
- Tail motor		1.51
- Speed reducers		9.20
- Cross-coupling lines		2.16
- Tail motor transmission lines		1.80
- Accessory gearcase		0.10
- Refrigerator		1.56/7.50 *
	Total	$22.13/28.07 \text{ ft}^3$

Electrical Speed-Reduction System

- Generators		6.12 ft^3
- Main motors		10.68
- Tail motor		1.51
- Motor coupling lines		4.08
- Tail motor transmission lines		1.80
- Cross-coupling lines		4.80
- Accessory gearcase		0.10
- Propeller supports		1.65
- Refrigerator		6.20/26.20 *
	Total	$36.94/56.94 \text{ ft}^3$

* Range of refrigerator volume reflects range of design weights.

7.4   Efficiency Comparison

Of primary concern when considering the efficiencies of different aircraft power transmissions is the weight penalty in fuel associated with the losses found in the different system. The electrical systems considered here have fewer losses associated with gears, bearings, and seals, but require that power be consumed in operating the refrigerator.

The losses are compared for the systems operating in the cruise mode, since almost all of the operation measured in time or fuel occurs in cruising. The cruise mode assumes that two turbines are driving four propellers.

The only losses considered are those which represent differences in the three systems compared.

Gear mesh inefficiency of 0.5 percent has been assumed. For bearings, a 0.2-percent inefficiency is assumed for bearings carrying tooth separating loads and 0.1-percent inefficiency is assumed for other bearings. Seals are assumed to have a constant friction torque of 10 inch-pounds. (These assumptions yield typical transmission efficiencies of better than 95 percent.)

The summarized differential losses are shown in Table X.

Table X

System Efficiency Comparison

Electrical reduction system		Losses (hp)
Refrigerator		292.0
Bearings		48.0
Seals		1.3
Gears		0.0
	Total	341.3
Electrical cross-coupling system		
Refrigerator		107.0
Bearings		144.0
Seals		3.7
Gears		90.0
	Total	344.7
Mechanical system		
Bearings		161.4
Seals		8.4
Gears		152.5
	Total	322.3

The difference in losses in these systems is very small. The 20-horsepower difference combined with a 0.5 pound per horsepower-hour specific fuel consumption yields a fuel consumption of 10 pounds per hour.

7.5   Reliability Comparison

7.5.1   Reliability

In the comparison of the relative reliability of the mechanical and the superconducting transmission systems, only those components directly affected will be considered. Devices common to all systems, such as the lubrication pumps, cooler, etc., are assumed to be equally as reliable for each system in spite of the fact that some of the details, such as load rating, may change.

The Poisson of exponential failure frequency distribution will be assumed to be sufficiently accurate for purposes of this first reliability comparison. As explained in detail in the References (47, 48, 49), the Poisson distribution, while representative for electrical equipment, is optimistic in describing mechanical equipment, which can generally be better described by a Weibull distribution having a shape factor greater than 1. The various parameters of the Weibull distribution are extremely sensitive to changes in conditions [50] and can lead to large errors if misinterpreted. Over short periods of time, however, the Poisson distribution is reasonably accurate and lends itself very readily to calculation of reliability and mean time between failure from tabulated failure rates for the various components and devices.

Tables XI and XII give a detailed breakdown of the "generic" failure rate (the failures associated with a class of machinery) for each of the devices for the mechanical and the electrical transmission systems. Refer to Figure 18 for the location and function of each device. The failure rates used were taken from Ref. 49 .

The actual failure rate is related to the generic failure rate by the ralation

$$F_r = G_r K_E$$

where

F_r is the actual failure rate

G_r is the generic failure rate

K_E is a modifier to adjust for the general environmental condition

Earles and Eddins [49] have determined that K_E = 50 is a generally representative value describing the condition of an aircraft in flight.

Table XI

Generic Failure Rates - Mechanical System Components

Part	Quantity	Failures/ 10^6 hrs	Total Failures/ 10^6 hrs
Propeller Gearcase			
Bearings	13	1.80	23.40
Seals	4	0.12	0.48
Gears	8	0.70	5.60
			29.48
T-Box			
Bearings	7	1.80	12.60
Seals	3	0.12	0.36
Gears	4	0.70	2.80
			15.76
Pivot Box and Accessory Gearcase			
Bearings	21	1.80	37.8
Seals	10	0.12	1.2
Gears	9	0.70	6.3
			45.3
Shaft Assembly			
Shaft	1	0.350	0.350
Bearings	5 (ave.)	1.800	9.000
Couplings	2	0.039	0.078
			9.428
Dog Clutch			0.350
Magnetic Clutch			0.6

Table XII

Generic Failure Rates - Electrical Systems Components

Part	Quantity	Failures/ 10^6 hrs	Total Failures/ 10^6 hrs
Motor/Generator			
Bearings	2	1.800	3.600
Seals	2	0.120	0.240
Windings	2	0.300*	0.600
Brushes	2	0.100	0.200
Couplings	2	0.039	0.078
			4.718
Propeller Gearcase			
Bearings	9	1.80	16.20
Seals	3	0.12	0.36
Gears	5	0.70	3.50
			20.06
Refrigerator			
Compressor	1	13.500**	13.500
Expander	2	10.000 ***	20.000
Heat Exchanger	4	5.000	20.000
Piping	13	0.224	2.912
			56.412
Auxiliary Turbine			10.0
Accessory Gearcase			
Bearings	10	1.800	18.000
Gears	5	0.700	3.500
Seals	5	0.120	0.600
Couplings	2	0.039	0.078
			22.178
Motor Contactor			0.75
Transmission Line			
Tubing	2	0.224	0.448
Seals	4	0.020	0.080
Conductors	1	0.190*	0.190
			0.718

*   Assumed 10 times normal conductors

**   Assumed equivalent to a pump

*** Assumed more than double a motor (2.13X)

Table XIII summarizes the generic failure rate, the actual failure rate, and the mean time between failures (MTBF) for the mechanical and the electrical transmission systems.

The system reliability can be determined for the case of the Poisson distribution by the relation

$$R(t) = e^{-t/m}$$

where

R (t)   is the reliability for a given period of time

t   is the time

m   is the mean time between failures

For the systems summarized in Table XIII, the reliability for a 100-hour period is, for the mechanical system,

$$R_M(100) = e^{-100/78.5} = .279 = 27.9\%;$$

for the electrical cross-coupling system,

$$R_{EC}(100) = e^{-100/97.7} = .361 = 36.1\%;$$

and for the electrical speed-reduction system,

$$R_{ER}(100) = e^{-100/124.3} = .447 = 44.7\%.$$

7.5.2   Safety

The reliability calculations of the previous section do not, however, completely describe the entire situation [51]. What they show is the probability of there being absolutely no failures in 100 hours of operation. In actuality, a number of items could fail in the course of a flight and not force the craft to crash. What is needed is a comparison of the probability that the system will maintain flight, without crashing, for 100 hours.

The diagrams of Figure 19 indicate the relation of the various devices to the entire system operation. The lines indicate a particular situation, such as the successful operation or failure of a part. The numbers in paraentheses are the probabilities of the particular situations' occurring. Each terminal point is marked as success (safe flight) or failure (catastrophe), and the probability of each success or failure has been calculated.

It has been assumed that 85 percent of the flight time is spent in the conventional, horizontal flight mode. In the vertical flight mode, any failure was considered catastrophic.

Table XIII

Systems Failure Summary

Component	Quantity	Failures/ 10^6 hrs	Total Failures/ 10^6 hrs
Mechanical Transmission System			
Propeller Gearcase	4	29.480	117.920
T-Box	1	15.760	15.760
Pivot and Accessory Gearcase	1	45.300	45.300
Shaft Assembly	8	9.428	75.424
Dog Clutch	2	0.063	0.126
Magnetic Clutch	1	0.600	0.600
			255.130
System generic failure rate		0.255×10^{-3}/hr	
Net failure rate		12.75×10^{-3}/hr	
System MTBF		78.5 hrs	
Electrical Cross-Coupling System			
Motor/Generator	5	4.718	23.590
Propeller gearcase	4	20.060	80.240
Refrigerator	1	56.412	56.412
Auxiliary turbine	1	10.000	10.000
Accessory gearcase	1	22.178	22.178
Motor contactor	1	0.750	0.750
Transmission line	15	0.718	10.770
			203.940
System generic failure rate		0.204×10^{-3}/hr	
Net failure rate		10.2×10^{-3}/hr	
System MTBF		97.7 hrs	
Electrical Speed-Reduction System			
Motor/Generator	9	4.718	42.462
Refrigerator	1	56.412	56.412
Auxiliary turbine	1	10.000	10.000
Accessory gearcase	1	22.178	22.178
Motor contactor	1	0.750	0.750
Transmission line	27	0.718	19.386
			151.188
System generic failure rate		0.151×10^{-3}/hr	
Net Failure rate		8.05×10^{-3}/hr	
System MTBF		124.3 hrs	
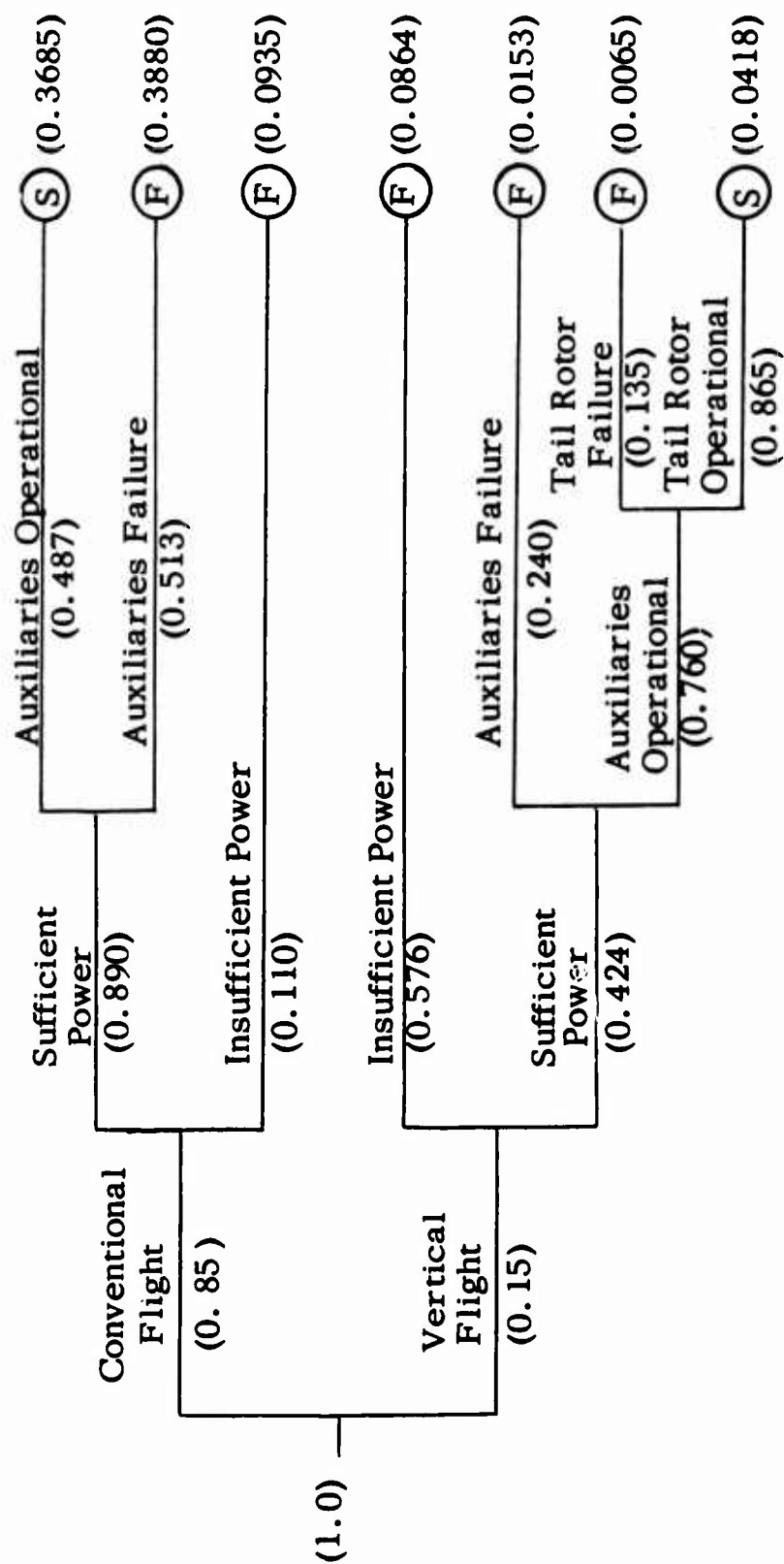
(a) Mechanical System

Figure 19. Safe-Flight Reliability Diagrams

R'_M (100) = 41.03%

(0.7214)

S — Auxiliaries Operational (0.852)

F (0.1252) — Auxiliaries Failure (0.148)

Sufficient Power (0.996)

F (0.0034) — Insufficient Power (0.004)

Conventional Flight (0.85)

F (0.0586) — Insufficient Power (0.391)

F (0.0351) — Auxiliaries Failure (0.384)

F (0.0022) — Tail Rotor Failure (0.038)

S (0.0541) — Tail Rotor Operational (0.962)

Auxiliaries Operational (0.616)

Sufficient Power (0.609)

Vertical Flight (0.15)

(1.0)

$R'_{EC}(100) = 77.55\%$

(b) Cross-Coupled System

Figure 19.   (Cont'd)

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Auxiliaries Operational
(0.622)   (S) (0.5230)

Auxiliaries Failure
(0.378)   (F) (0.3180)

Sufficient
Power
(0.989)

Insufficient Power
(0.011)   (F) (0.0090)

Conventional
Flight
(0.85)

(1.0)

Insufficient Power
(0.468)   (F) (0.0702)

Auxiliaries Failure
(0.384)   (F) (0.0306)

Tail Rotor
Failure
(F) (0.0019)

Auxiliaries
Operational
(0.616)

Tail Rotor
Operational
(S) (0.0473)

Sufficient
Power
(0.532)

Vertical
Flight
(0.15)
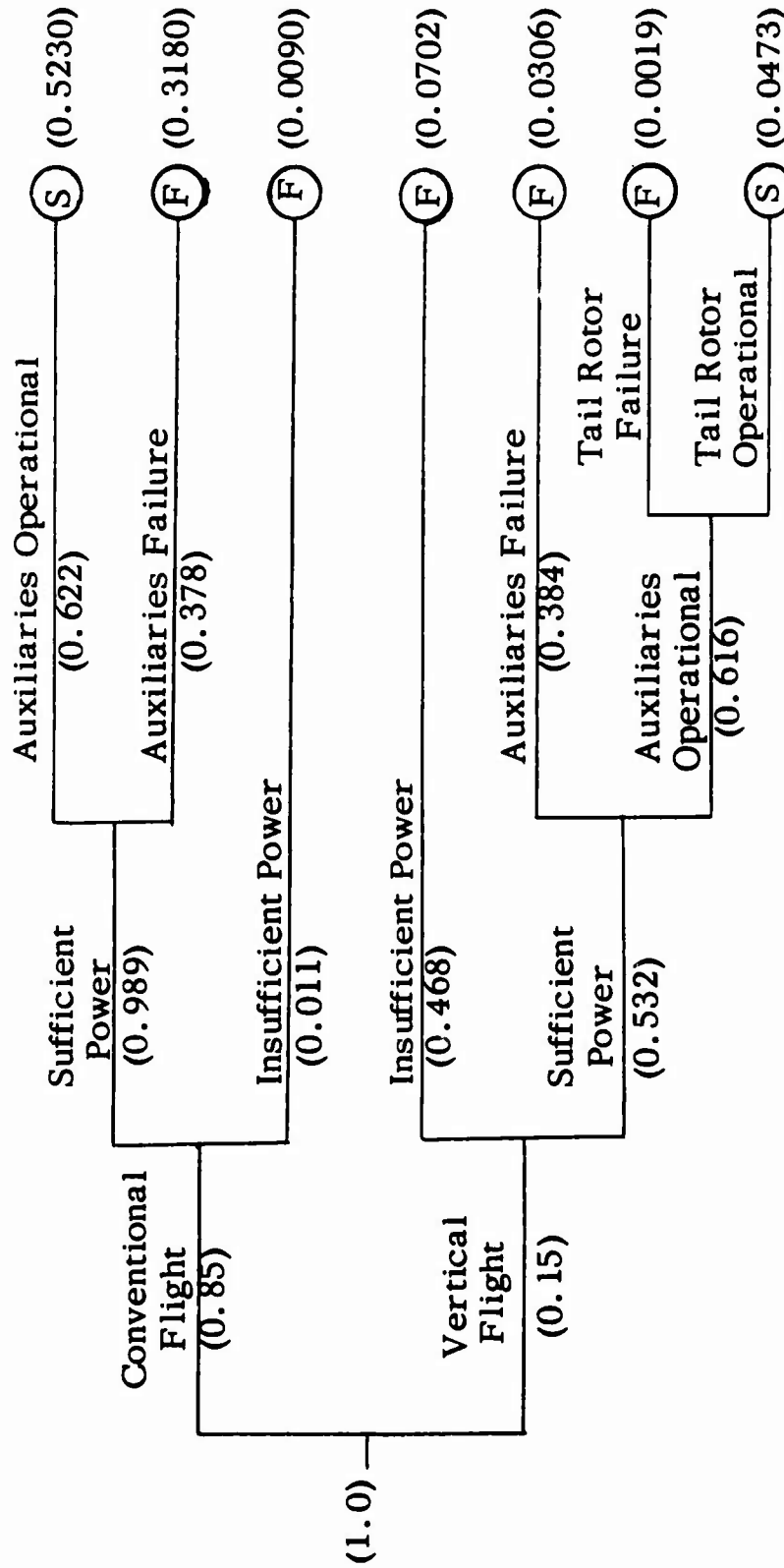
R'_{ER} (100) = 57.03%

(c) Electrical Speed Reduction System

Figure 19.   (Cont'd)

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Summing up the successes of the three systems gives a new reliability figure which includes the possibility of non-catastrophic failures:

$$R'_M (100) = 41.03\%$$

$$R'_{EC} (100) = 77.55\%$$

$$R'_{ER} (100) = 57.03\%$$

In the superconducting electrical transmission systems, the lack of dyanmic mechanical connections suggests the possibility of isolating the refrigeration unit from vibrations and perhaps reducing the environmental factor, K_E. As the refrigerator is the least reliable of all the devices in the system, such a reduction would be very significant.

Another possible advantage for the electrical systems may result by duplication of the transmission lines. However, additional valves would perhaps be required to seal off leaks in the damaged lines. These extra items would decrease the reliability. A more detailed examination would be required to determine if redundancy would in fact increase the reliability and safety of the system.

7.5.3 Maintainability

Maintenance problems unique to the superconducting transmission system are those relating to the cryogenic refrigeration system, to the evacuated thermal insulating arrangement, and to the superconducting devices. New techniques are being developed to quantitatively predict maintainability and availability (52, 53); however, presently these methods require more detailed information on the design and the repair times of the various components. A qualitative comparison would appear more meaningful at this time.

The use of cryogenic refrigerators and of vacuum systems has become commonplace, and techniques for inspection and repair are becomming well developed. The experience gained on operational cryogenic refrigerators indicates that adequate preventative maintenance procedures can be developed to ensure reliable system performance.

The vacuum insulation arrangement is a completely static system, and save for abnormal situations there is little opportunity for problems to develop at any specific frequency.

The maintenance of the superconducting devices is another matter. Superconductivity is still a relatively new, developing field, and techniques for the manufacture, use, and repair of superconductors are incomplete. Here again, however, the superconductor is static and should require special attention only under abnormal circumstances. Adequate methods of repair have not yet been developed, and therefore under such circumstances damaged items must be replaced completely.

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Referring to Table XIII, it is seen that the least reliable devices of the mechanical system are the shaft assemblies and gearcases. From Figure 18, these devices are seen to be fairly well distributed throughout the aircraft. For the electrical transmission system, on the other hand, the worst problems are located in the refrigeration system. Thus, a large part of the maintenance procedure is concentrated in one area, and it suggests increased accessibility and shorter downtime for maintenance of the electrical system.

7.6 Readiness - System Cool-Down

One measure of the effectiveness of a system for use in a military aircraft is the length of time required to prepare it for operation and the weight penalty for fuel or equipment required for these preparations. For a purely mechanical system, the preparations would involve the pre-flight checkout. For the superconducting system, in addition to the pre-flight checkout, it is also required to cool the entire system down to operating temperature. The cool-down and the checkout can proceed concurrently, however, and if the cool-down time is not extreme this may not impose a penalty on the system.

To get a quantitative feel for the cool-down times associated with an actual system, a detailed evaluation of one particular system design was performed. The system design investigated approximates the specifications of the XC-142A V/STOL experimental aircraft as described in Section 7.1 of this report. Two arrangements of this system were considered, one providing for electrical cross-coupling only and the other also providing for electrical speed reduction. Details of the cool-down calculations are found in Appendix III.

Table XIV summarizes the data and results of the cool-down investigation of the two superconducting electrical transmission systems. The range in cool-down times reflects the range of refrigerator design weights. The least optimistic cool-down times for both systems are less than 30 minutes, which for most situations should be satisfactory.

Using typical values for the specific fuel consumption [54] of the auxiliary turbines used to power the refrigeration systems, the weight penalties for the electrical systems' cool-down are:

Electrical Cross-Coupled System

$$130 \text{ horsepower } \times 1.13 \frac{\text{pounds fuel}}{\text{horsepower-hour}} = 147 \frac{\text{pounds}}{\text{hour}}$$

Electrical Speed-Reduction System

$$560 \text{ horsepower } \times 0.64 \frac{\text{pounds fuel}}{\text{horsepower-hour}} = 358 \frac{\text{pounds}}{\text{hour}}$$

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Table XIV

Superconducting Systems Cool-Down Time

	Cross-Coupled Only			Electrical Speed Reduction		
Normal operating refrigeration load [Btu/hr]	1280			6090		
Normal power requirement [hp]	130			560		
1 COP at 10° K	260			235		
Cold-end temperature range [° K - ° K]	300-200	280-80	80-10	300-200	200-80	80-10
Average gross refrigeration capacity [Btu/hr]	90,000	37,000	6,700	428,000	169,000	29,000
Average non-operating loss [Btu/hr]	360	850	590	650	1530	1040
Average net refrigeration capacity [Btu/hr]	89,640	36,150	6,110	427,350	167,470	27,960
Enthalpy integral* [Btu]	6900/11000	4670/7420	580/670	26000/40000	17500/26900	2200/2500
Cool-down time [hr]	.069/.122	.130/.206	.095/.11	.061/.094	.105/.094	.079/.089
Total cool-down time, 300° K to 10° K [hr]	.294/.438			.245/.344		

* Range of enthalpy integral reflects range of refrigerator design weights.

7.7 Cost Comparison

At the present time, the mechanical transmission system is in an experimental stage of development, the first ascent of the XC-142A having occurred only within the last year. The superconducting systems are only in the conceptual and preliminary design stages. The major components have never been built and operated even experimentally. As a result, it woud be meaningless and misleading to attempt a comparison of relative costs of these systems at this time other than to say that in all probability the superconducting systems will be somewhat more costly than the mechanical system.

7.8 Effect of State-of-the-Art Advancements

Stated in the greatest degree of generalization, there are two factors which limit the promise of superconducting electrical machinery: (1) the superconductors as presently known must be operated at cryogenic temperatures, and (2) the superconductors generate heat (have losses) when operated in the presence of varying magnetid fields or with alternating electrical currents. As a consequence, the most dramatic advancements in the state of the art can be expected in the areas of reduction of AC losses, increase of allowable operating temperature, and reduction of refrigerator weight.

AC Losses

Losses in the superconductor are generated by three mechanisms: (1) hysteresis losses in the actual superconducting film, (2) eddy losses in the substrate, and (3) eddy losses in the protective plating covering the superconductor. A study by H. London (3) related the hysteresis losses per unit volume of superconductor to the magnetic field strength and frequency, the critical current desnity, and the thickness of the superconducting film. The curve labeled "London" in Figure 20 shows the hysteresis loss relative to the loss of presently available material as a function of the relative thickness of the superconducting film. The lower limit of the film thickness is determined by the diffusion of the substrate into the film. This diffusion spoils the superconductivity of the intermediate, diffused layer. The minimum practical thickness is on the order of 0.025 mil, or one-tenth the thickness of commercially available materials.

The substrate eddy loss is a relatively minor factor, as shown by the curve labeled "London and Substrate" in Figure 20. The substrate is made of a material having high resistivity in order to minimize these eddy losses.

The loss in the protective plating becomes more significant as the superconducting film thickness decreases. The protective plating serves three purposes: (1) it is a safety feature to provide for more gradual dissipation of energy in the event of a "quench", (2) it protects the superconductor from physical damage during handling, and (3) it reduces the low field current instability (61). The 0.5 mil plating thickness now used is about optimum. The curve labeled "Total" in Figure 20 indicates the strong influence of the plating eddy losses for thin superconductors.

Curves based on RCA No. 60214
superconductor (0.25-mil thickness,
0.5-mil silver plating). Current
density and circuit current held
constant.

Total

London and Substrate

London

Silver Plating Eddy Loss

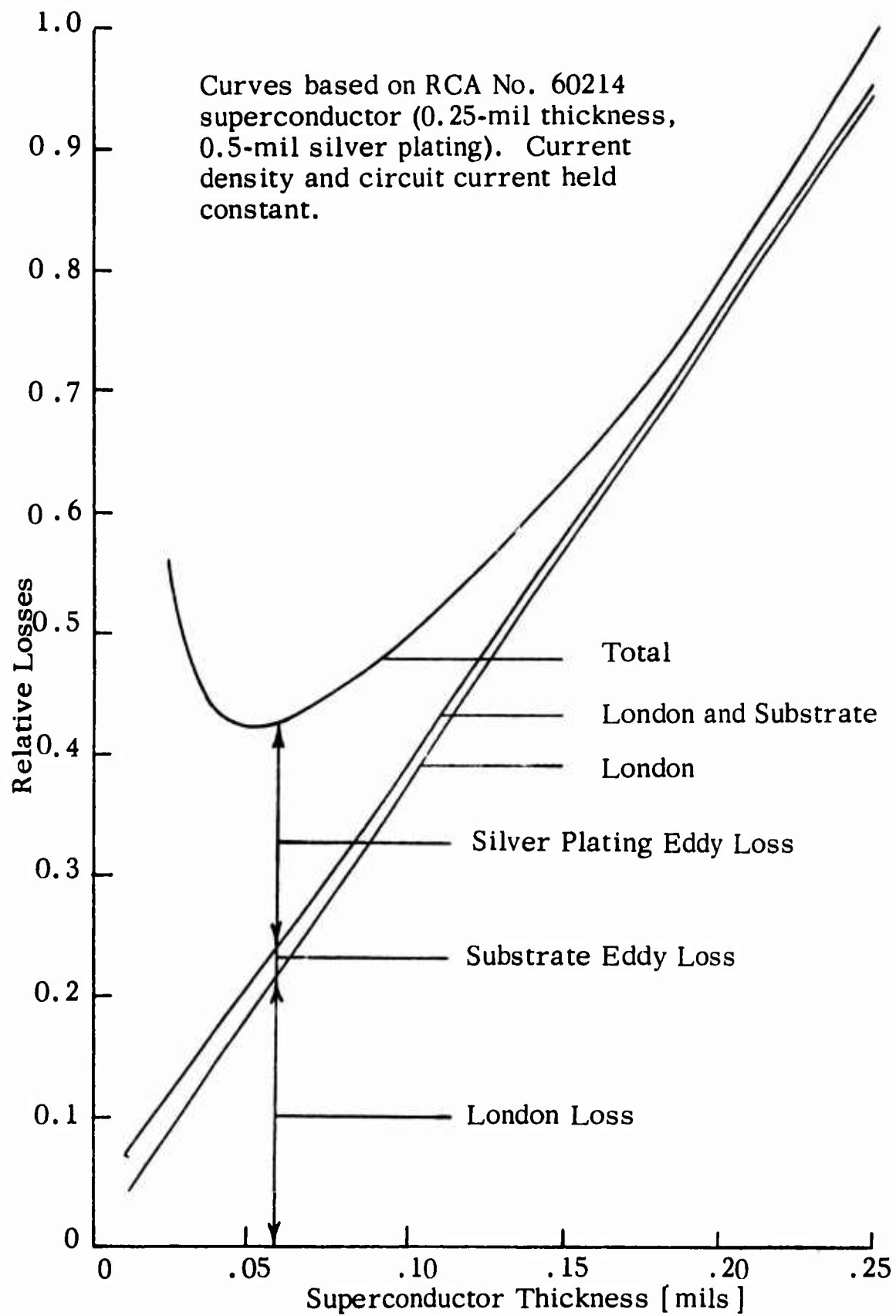Substrate Eddy Loss

London Loss

Figure 20. Superconductor Losses

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The optimum superconductor thickness is about 0.052 mil, which is a reasonable thickness as far as manufacturing is concerned. At the optimum, the relative loss if 0.43.

Operating Temperature

A limited study by Wisseman, Boatner, and Low [6] implied that in the region below $4.2°$ K the AC losses decrease as the 2.5 power of the temperature for Nb-Zr alloys. The study did not consider higher temperatures or other materials. From Figure 6 of Section 3.2, the refrigerator weight is found to vary as the -1.8 to -2.83 power of the temperature in the 5° K to 10° K region for a 1000-watt refrigerator. If the Wisseman loss relation can be assumed to hold for the intermetallic compounds and at the higher temperatures, it is a standoff as far as system weight is concerned and there is no incentive to operate at lower temperatures.

Another trend of thought currently receiving much attention is the elevation of operating temperature, perhaps even to room temperature or above (see Section 3.1). Present indication is that for the metallic superconductors, the upper critical temperature limit is about 20° K, or about where the present intermetallic compounds are. As for room temperature superconductors, they have been described theoretically (see Section 3.1), but the realization of such a breakthrough of necessity cannot be predicted. The consequences of course, the elimination of the refrigeration unit, are obvious. The advantages of such a system over the mechanical equivalent system are inestimable without a major revision of the basic design criteria concerning the efficiency and weight, and their optimization, used on the present generation of superconducting machines.

Refrigeration

The most recent advancement in refrigerator design, the change to turbo-compressors and expanders, is reflected in the lower limit of weight in Figure 6, Section 3.2. Also, the most advanced methods of compact heat exchanger design were employed. Except for some unexpected breakthrough, in the form of a revolutionary new thermodynamic cycle or an entirely new refrigeration concept, it is difficult to predict a reduction in refrigerator weight greater than the 15 percent specified in Section 3.2.

Figure 21 is a comparative summary of the net effect of state-of-the-art advancements on transmission system weights. Extrapolation of present weight trends of mechanical devices indicates a probable reduction of at least 10 percent in the weight of mechanical components for all systems. This factor is included in the projection of system weights in Figure 21.
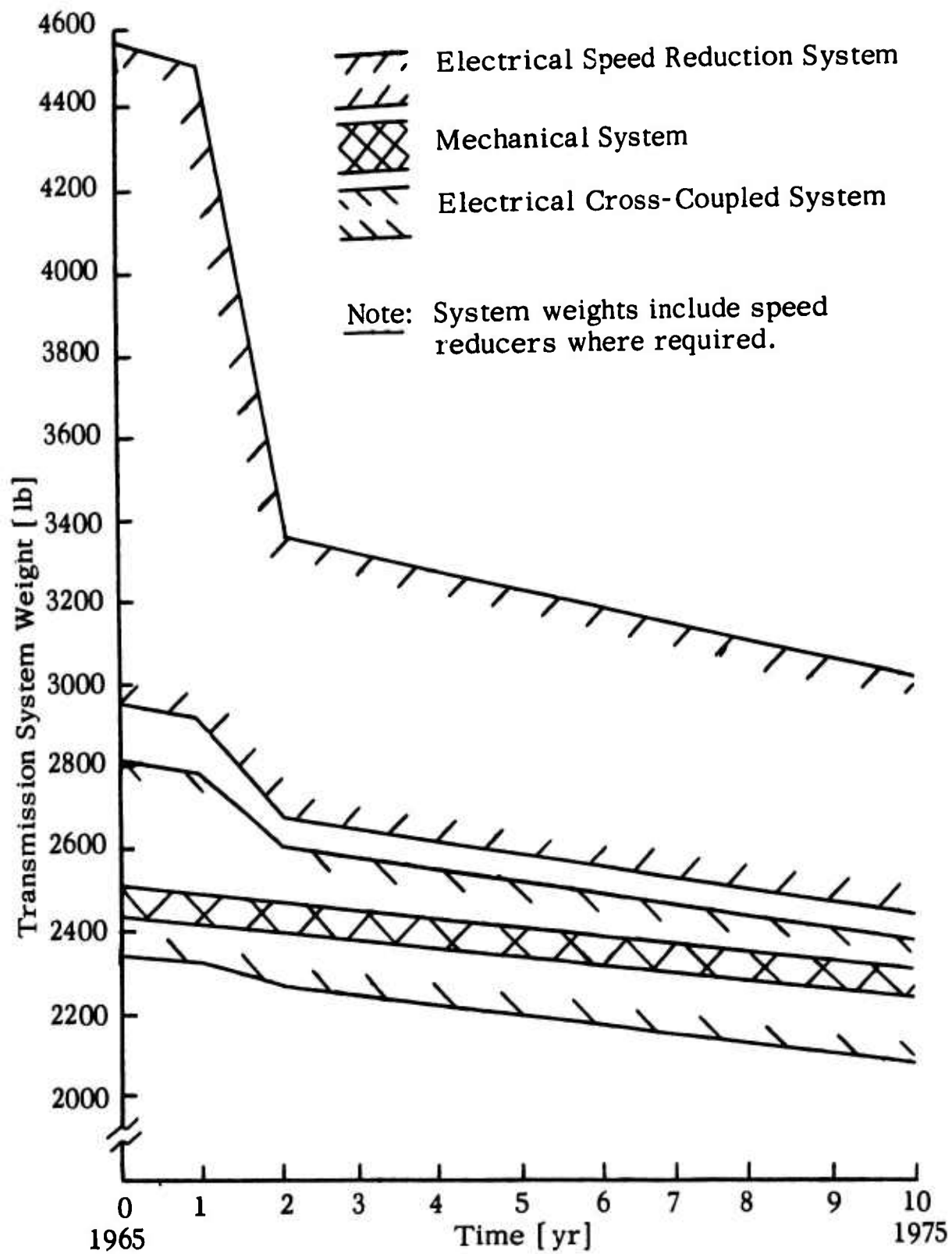
71

Figure 21. Effect of State-of-the-Art Advancements

72

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APPENDIX I

MOTOR/GENERATOR DESIGN CALCULATIONS

Electrical Design

The fundamental specifications for the electrical devices used in the superconducting electrical transmission system are given in terms of the power (W_0), operating speed (N), and number of magnetic poles (P). The independent design parameters are the operating line-to-line voltage (E), the number of phases, the connection arrangement (delta or wye), the magnetic flux density (B), the magnetic gap (δ), and the armature tooth-to-slot width ratio (r). Other combinations of independent design variables are possible, but this combination facilitates rapid design and emphasizes the effects of certain critical parameters.

For this study it is assumed that all designs use three-phase, wye-connected circuits. The use of three phases makes for more economical utilization of the winding space and offers possibilities for shaping of the output waveform. For a given power and line-to-line voltage, a wye-connected device operates at a lower winding current. It also more effectively limits the short-circuit current.

Having selected the desired operating magnetic flux density, the current-carrying capacity of the superconductor windings can be determined from manufacturers' data for the material selected. Figure 22 is a representative example of a currently available material, [55] derated to allow for the operating temperatures expected in an actual device.

The peak radial magnetic field strength generated by a superconducting field at the center of the pole at a distance δ from the surface of the pole was determined by integration of the incremental contributions over the cross section of field winding. The result of this integration for the idealized case (winding form omitted) for a P-pole field is

$$B = \left(\frac{\mu_0 J}{4\pi}\right) F_w D_e \frac{x^2}{2} \ell n \left[1 + \frac{2(1-\cos\theta)x}{(1-x)^2}\right] - \frac{\cos 2\theta}{2} \ell n \left[1 - 2x\cos\theta + x^2\right]$$

$$+ \sqrt{2(1-\cos 2\theta)} \cos\theta \left[\tan^{-1}\sqrt{\frac{2(x-\cos\theta)}{1-\cos 2\theta}} - \tan^{-1} - \frac{\sqrt{2}\cos\theta}{1-\cos 2\theta}\right.$$

$$\left. + \ell n (1-x) + (1-\cos\theta) x \right\}$$

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Based on preliminary information bulletin for
RCA No. 60214 Nb3Sn Ribbon operating at 4.2°K,
derated by approximately a factor of 3 for operation
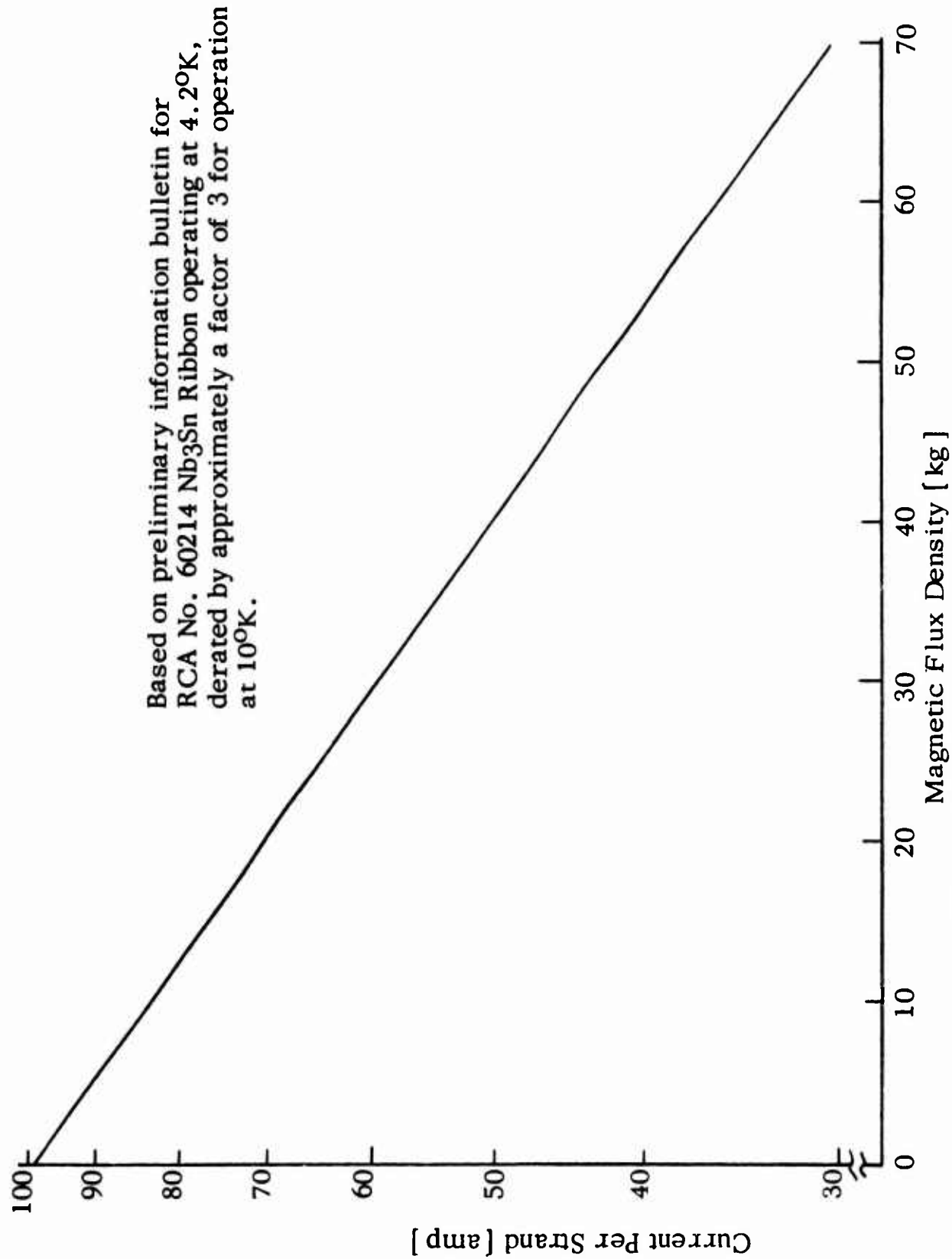at 10°K.

Figure 22. Superconductor Current Rating

80

where

μ_o is the magnetic permeability of air

J is the current density

F_w is the winding or packing factor

D_e is the effective diameter to the center of the armature winding

$x \quad = \quad D/D_e$; D is the field winding diameter

$$\theta \quad = \quad \begin{cases} \pi/P & \text{for } P > 2 \\ \pi & \text{for } P = 2 \end{cases}$$

When corrected to account for the winding form, the peak radial field strength as a function of field diameter for a 2-pole rotor ($J = 2 \times 10^8$ amp/m^2; $F_w = 0.5$; $\delta = 0.150$ in.) is as shown in Figure 23. The above equation agrees very closely with the experimental results reported in Reference 5.

The field strength for P-poles relative to that for 2-poles as a function of field diameter is given in Figure 24.

The magnetic gap is selected as small as possible to take advantage of the higher field strength close to the surface of the field. It is limited by the rapid increase of windage loss as the gap is decreased.

The length of conductor per phase $(L_p)'$ is determined by the standard generator relation $E = B \, L_p \, V$.(56). Knowing this length, the active armature length (L) can be determined from the geometric relations for the winding arrangement and winding form design.

Determination of Losses

The principal losses contributing to the refrigeration load are:

(1) Hysteresis losses in the superconductor
(2) Windage losses
(3) Electrical lead losses
(4) Conduction and radiation losses through the support
structure and insulation

Hysteresis losses in superconductors have been analyzed by H. London (3). For a thin strip of thickness t, it is found that the power loss per unit volume of superconductor is approximately

$$q = J_c H_{max} \, t \, F$$

where H_{max} is the maximum magnet field and F is the frequency. The benefit derived by the use of extremely thin ribbon superconductors is readily apparent from the linear dependence of the losses on t.

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$$I = 2 \times 10^8 \text{ amp/m}^2$$
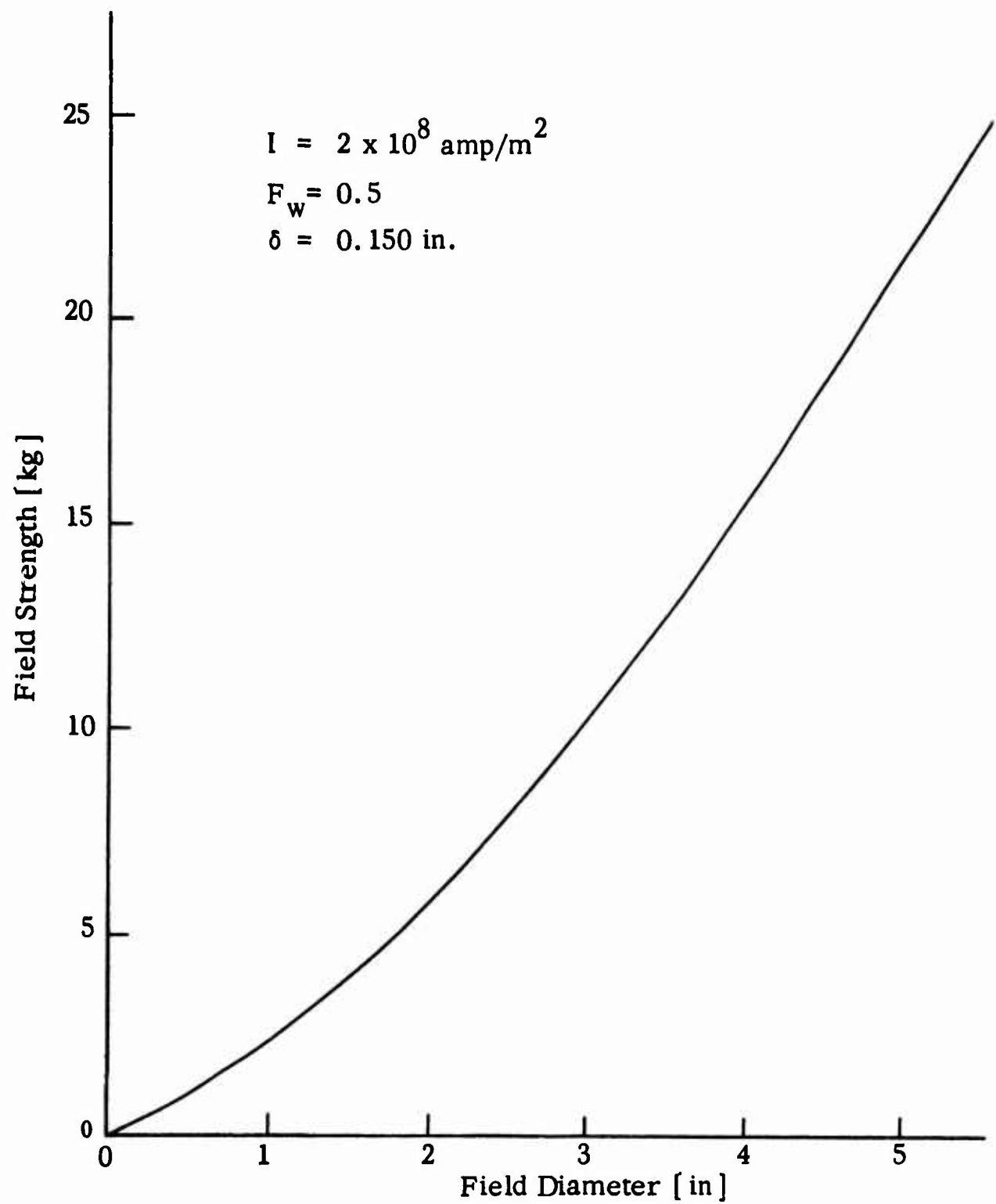$$F_w = 0.5$$
$$\delta = 0.150 \text{ in.}$$
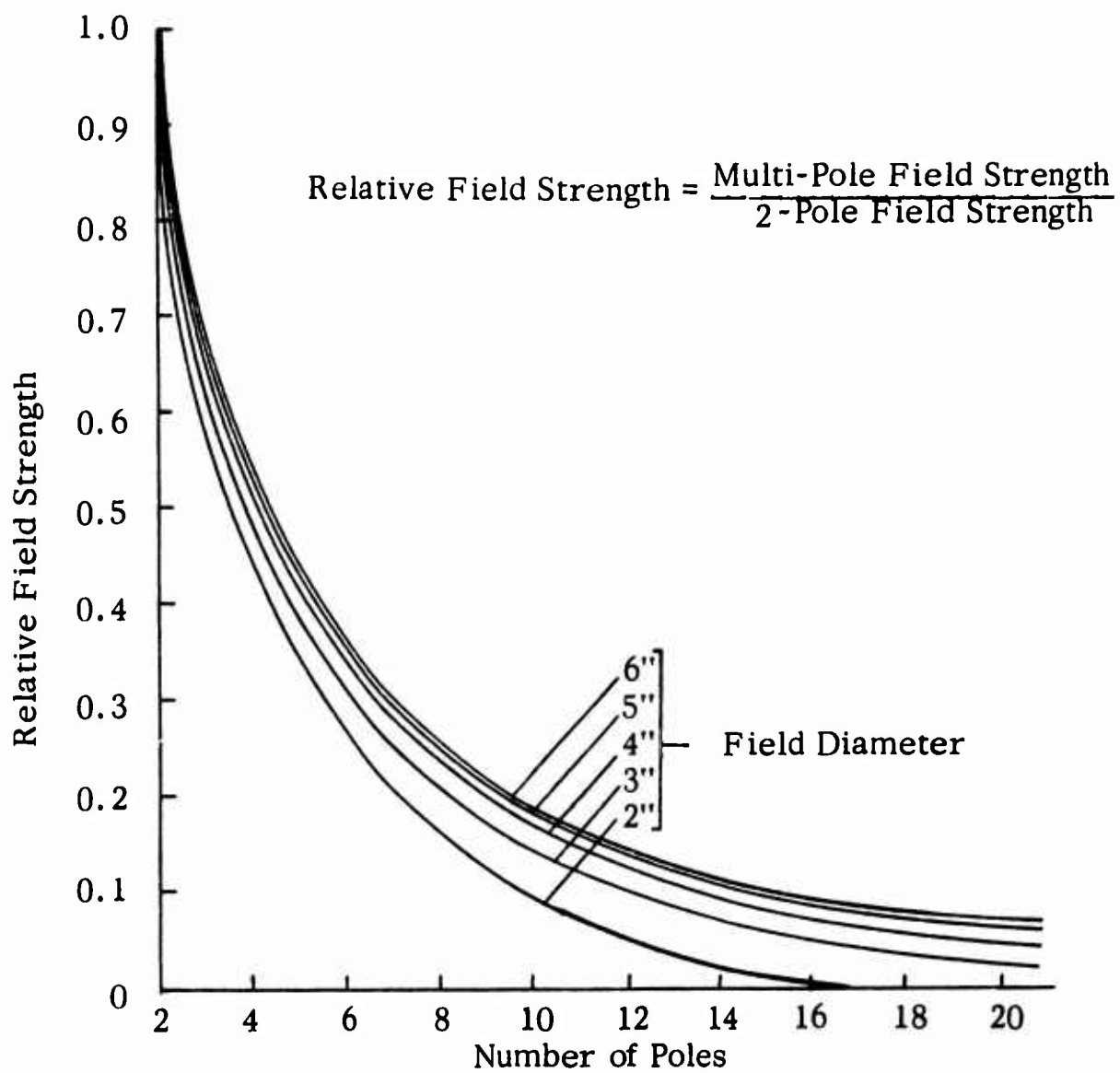
Figure 23.   2 -Pole Field Strength

Figure 24. Multi-Pole Relative Field Strength

The windage (fluid friction) loss is the result of the viscous drag force from the helium in the gap between the rotor and the stator. The analysis is not simple, and several different assumptions can be used to describe the loss. It is reasonable to assume turbulent Couette flow with velocity profiles at the walls similar to those which would be observed between two flat plates. Assuming the friction factor to be given by [57] $F = 0.045/(Re)^{0.25}$, the shear stress at the wall is given by

$$\tau = F \frac{\rho V^2}{2 g} = \frac{0.045 \, \rho V^2}{(Re)^{0.25} 2 g}$$

where ρ is the density and Re is the Reynolds number. The velocity to be used here is the centerline velocity in the gap between the rotor and stator, and is equal to one-half the rotor surface speed. The power which the shaft imparts to the fluid is equal to the product of the shear stress, the rotor surface area, and the rotor surface velocity.

One-dimensional heat transfer equations applied to conduction of heat through an electrical lead carrying a current with the ends held at specified temperatures is given by the equation [5]

$$q_L = \sqrt{q_H^2 + 2 I^2 \int_{T_C}^{T_H} \rho k \, d T}$$

where

I	is the current
ρ	is the electrical resistivity at temperature T
k	is the thermal conductivity at T
q_H	is the heat entering at the hot end (zero for minimum q_L)
T_H T_C	are the hot- and cold-end temperatures

The optimum lead is therefore one which has the minimum integral of $\rho k \, d T$ over the specified temperature range.

Conduction and radiation losses through the support structure, shaft, and insulation are calculated using standard heat transfer relations; see, for example, Rohsenow's and Choi's Heat, Mass and Momentum Transfer [58].

Weight Estimation

Having determined the general design of the motor, the actual weight of the major component (windings, shaft, chamber, bearing assemblies, etc.) was calculated in terms of the armature active length and the diameter of the field. Summing up the contributions from all these components for the various L and D, and introducing an arbitrary multiplier of 1.2 to account for miscellaneous hardware, an approximate relation for the motor weight was determined as

$$w_M = (0.9L + 8.27) D^{1.3} + 28$$

Over the limited range of L and D of interest to this study, the above equation should be reasonably accurate as a first approximation.

Appendix II

SYSTEM CONTROL ANALYSIS

For the purpose of this simplified analysis, it will be assumed that:

(1) Synchronous reactance is a linear effect; i.e.,
the actual armature reaction and leakage re-
actance are linear and "vector additively coin-
cident effects."

(2) Resistance is of negligible effect, even for very
low speeds, and that no AC resistance effects
may be considered in the interconnecting (super-
conducting) cables.

(3) Some devices can be used to determine current
balances, e.g., some type of current transformer,
etc., which will be sufficiently small in dissipation
to still allow assumption (2) to be true.

Now we define

(a) Frequency: $f = \dfrac{p\,N}{120}$ p = poles
N = speed (rpm)

(b) Voltage: $E = k_1\, f\, \Phi$ Φ = flux/pole

(c) Reactance: $X = 2\,\pi\, f\, L_e$ L_e = effective inductance

$\qquad\qquad\qquad = k_2 N$

Short Circuit

$$I_s = \frac{E}{X} = \frac{K_A\, N\Phi}{K_2 N} = \frac{K_A}{K_2}\, \Phi \qquad \text{(This is the short-circuit current)}$$

Thus

$$I_s \propto \Phi \text{ and is independent of speed.}$$

Parallel Operation of Two Machines

(a) Assuming the same load angle but different excitation
(see Fig. 25a),

Resultant voltage = $E_1 - E_2 = E_R$

Circulating current = $E_R/2X$ lagging by 90°

(b) Assuming the same excitation but different load angles (θ) (see Fig. 25b),

$$E_R = 2 E \, \sin \left(\frac{\theta}{2}\right)$$

I lags E by $\frac{\theta}{2}$

Now assume that θ is small; then $E_R = E\theta$.

$$I = \frac{E_R}{2X}, \quad \underline{almost} \text{ in phase with E;}$$

$$\therefore \quad \text{Power} = EI = \frac{E^2 \theta}{2X}.$$

$$\text{Torque} = \frac{E^2 \theta}{2XN} = K_3 \frac{(N\Phi)^2 \theta}{(N) \, N} = K_3 \, \Phi^2 \theta$$

Thus we have two important results:

$$I = K_4 \, \Phi \, \theta$$

$$T = K_3 \, \Phi^2 \, \theta$$

That is, current and torque are $\underline{also}$ independent of speed.

These results show that the load angle affects current and torque in the same ratio; this would be fine if a single machine could supply all the other machines in parallel, but we would be overdesigning if we did this, so we will use the parallel operation only for major runup to keep in synchronism.

Suppose the torque speed curve is as shown in Figure 26 (i.e., the load is mainly aerodynamic of a "power" type); e.g., suppose we have four in parallel, then one generating must supply three motoring. Suppose we rate the machines (at less than maximum by some ratio to allow for instantaneous transient currents) at a current I_R; then the maximum torque we can use is that of $1/3$ I. Thus $I_R' = 1/3 \, I_R$

$$I_R = K_4 \, \Phi_R \, \theta_R \qquad T_R = K_3 \, \Phi_R^2 \, \theta_R$$

$$T_R = \left(\frac{K_3}{K_4}\right) \Phi_R I_R$$
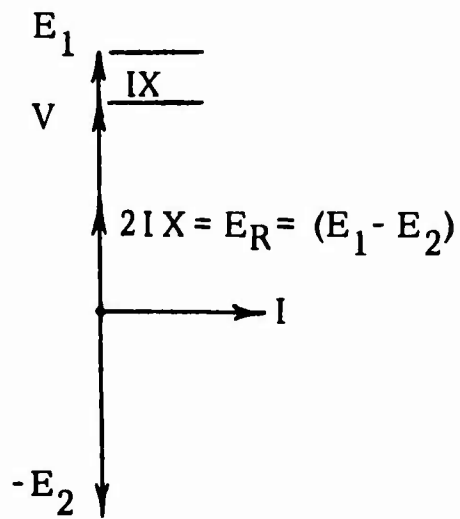
(a) Same Load Angle,
Different Excitation
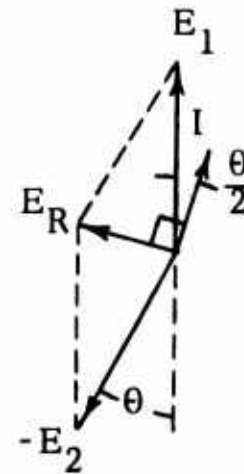
(b) Same Excitation,
Different Load Angle

Figure 25. Phasor Diagrams - Parallel Operation
of Two Machines

Figure 26. Typical Torque-Speed Curve

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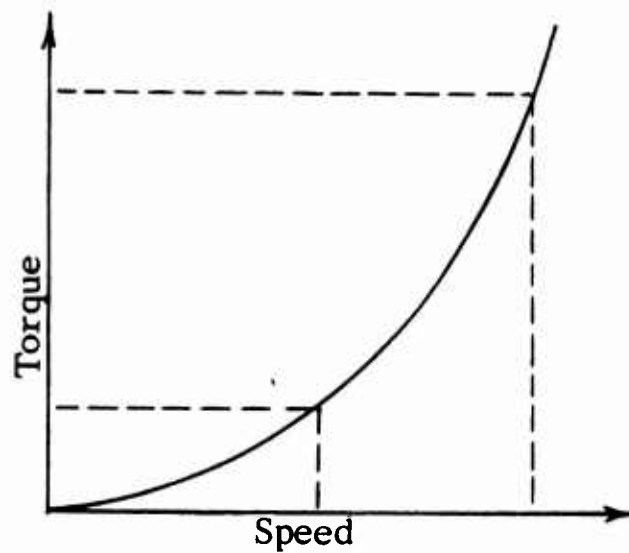$$I_R' = \frac{1}{3} I_R \qquad \therefore \qquad T_R' = \left(\frac{K_3}{K_4}\right) \Phi_R' I_R' = \frac{T_R}{3} \frac{\Phi_R'}{\Phi_R}$$

$\therefore$ Unless we can increase $\Phi_R' > \Phi_R$, which is not sensible, since we should be operating as near maximum as possible for economical design, we have

$$T_R' \approx \frac{T_R}{3}$$

Note that if the torque/speed curve is of the form (such as power 3)

$$T = K_5 N^3 ,$$

then

$$T_R' = \frac{1}{3} T_R \qquad \therefore \quad (N_R')^3 = \frac{1}{3} (N_R)^3$$

$$\therefore N_R' = \frac{N_R}{\sqrt[3]{3}} \approx .7 \, N_R.$$

That is, we can only go to 0.7 speed with a <u>single</u> machine acting as a generator and the others motoring.

Thus, above about two-thirds speed, we should make sure that either

(1) The control keeps the driving turbine governor down below two-thirds speed until the other turbines start to load share, or

(2) The flux must be dropped off to keep the current low, or

(3) Combinations of the above, or

(4) The blades must be feathered to keep torque always less than one-third full rated value.

BUT: Note the problem, for if the flux is dropped off <u>unevenly</u> on the machines, then we have merely zero torque circulating current as in (a) above.

Appendix III

SYSTEM COOL-DOWN CALCULATIONS

The major items affecting the cool-down of a superconducting system are:

(1) Refrigeration capacity as a function of the cold-end temperature

(2) Heat losses into the system (non-operating losses) as a function of temperature

(3) System enthalpy as a function of temperature

The "off design" performance of the cryogenic refrigerator is a very complicated matter and would require extreme detail of design and operating conditions for complete evaluation. A reasonable first approximation is to consider the refrigeration capacity to be a constant fraction of the Carnot performance during cool-down. This results in the relation

$$ q_o = N_R W_R \frac{T_c}{T_o - T_c} $$

where

q_o is the refrigeration capacity

W_R is the refrigerator compressor power

N_R is the fraction of Carnot performance

T_o is the heat-rejection temperature (ambient)

T_c is the cold-end temperature

The normal operating refrigeration capacity is determined as that required to maintain operation under the most severe emergency condition. The normal operating power requirement can then be calculated from the COP such as that given in Figure 13. The fraction of Carnot performance, N_R, is assumed to be 0.1, the ambient temperature is 300° K, and the normal operating cold-end temperature is 10° K. The refrigeration capacity as a function of temperature is then calculated using the above equation.

The non-operating losses into the system are the conduction losses through the shaft and support members and the radiation losses through the

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insulation and vacuum. By proper design, the conduction losses can be made reasonably small at the operating temperature; however, the thermal conductivity increases rapidly with temperature [59] and the net conduction heat loss is significantly increased above the operating temperature. The non-operating losses as a function of temperature are given in Table XV.

Table XV

Non-Operating System Losses

Component	10° K	80° K	200° K	
Motors and Generators	25	190	140	$\left[Btu/hr\right]$
Transmission Lines	0.230	0.175	0.080	$\left[Btu/hr\text{-}ft\right]$

An accurate calculation of the enthalpy of the various components would require a detailed design for each component. However, by making some assumptions about the proportion of the total component that is cooled to various temperatures, a rough first approximation can be made as shown in Table XVI.

Table XVI

Enthalpy Integral of Components
$\left[Btu/lb\right]$

Component	80° K–10° K	200° K–80° K	300° K–200° K
Motors and Generators	0.95	6.75	10.1
Refrigerators	0.20	5.8	8.5
Transmission Lines	1.11	7.79	11.1

An exact calculation for the cool-down time would require solution of the equation

$$t = - \int_{T_i}^{T_F} \left(\frac{1}{q_o - q_L} \right) \, d\,Q\,(T)$$

where

t is the cool-down time

q_o is the refrigeration capacity

$q\,L$ is the heat loss rate

T_i is the initial temperature

T_F is the final temperature

$d\,Q\,(T)$ is the change in enthalpy of the system as a function of temperature

with q_o, q_L, and dQ all functions of the temperature. Only q_o is given explicitly in terms of temperature. Therefore, rather than trying to get q_L and dQ in terms of temperature to solve the cool-down equation, a sufficiently accurate first approximation can be obtained by assuming linear dependence of q_L and dQ on temperature and performing a piece-wise calculation for the time.

For calculation of warm-up times for the various components, the same equation is valid as was specified above for cool-down but with q_o equal to zero. The same piece-wise linear solution can be used for computing warm-up times.

One further assumption that has been made concerning the cool-down of the system is that all the components cool down at the same rate.

Appendix IV

CRYOGENIC MACHINES

Introduction

Conventional copper-wound machines operating at room temperature generally operate at heat transfer limited current densities. The relation of maximum current density to the maximum allowable temperature rise is given by the relation

$$J_{max} = \sqrt{\frac{2 h \Delta T}{\lambda \rho d}}$$

where h is the heat transfer coefficient, ΔT is the temperature rise, λ is the packing factor, ρ is the resistivity, and d is the winding slot depth. Typically, J_{max} for conventional machines is of the order 10^3 amperes per inches squared. This in turn dictates the specific size and weight of a machine.

By operating a copper-wound machine at cryogenic temperatures, the losses may be reduced by one or even two orders of magnitude. This results from the strong dependence of the resistivity of copper on the temperature [60]. Consequently, higher current densities can be used and a more compact design is possible.

However, at low temperatures, factors other than heat transfer tend to dominate the picture. First among these is the specific weight of present state-of-the-art refrigerators. This factor makes it advantageous to operate a motor at a current density which produces the minimum total iron (eddy) and copper (resistance) losses.

The iron losses, on a per-pound basis, increase slightly as operating temperatures drop, but may be considered constant over the range of temperatures from 20° K to 77° K, the region of primary interest. The additional losses contributed by stray eddies, windage, etc., have also been considered constant in the 20°-77° K region.

The typical design specifications for a motor fix the power, speed, voltage, and frequency at which the motor is to operate. The designer must then produce a unit meeting these specifications which has a minimum weight and/or a maximum efficiency. For the present, we will look only at the minimum weight aspect of the problem.

Analysis

The design specifications for an electric motor or generator fix the rated power (W_o), the operating voltage (E), the speed or angular velocity (ω), and the frequency (F). From practical considerations, other parameters are

also held constant: the flux density in the teeth (B_T) held just below saturation the rotor diameter (D) limited by the allowable stress, the windage gap (δ) to maintain 100-percent synchronous reactance, and the ratio of tooth width to slot width (r) assumed equal to one as a reasonable first approximation.

As a consequence of the above, it can be shown that the armature current (I_a) is a constant and that the average magnetic flux density in the gap (B_g) is constant.

From the standard voltage equation

$$E = B L V$$

where B is the peak magnetic flux density, L is the length of conductor per phase, and V is the electric velocity, it is found that in terms of the above constants,

$$E \propto B_g L \omega D.$$

Therefore, L is also a constant.

The electrical losses in the machine are the resistance loss in the conductor (Q_R), the hysteresis loss in the teeth (Q_T), and the hysteresis loss in the iron core magnetic return path (Q_c).

$$Q_R = I_a^2 R = J_a^2 A_a \rho L \propto \rho/A_a$$

where J_a is the armature current density, A_a is the cross-section area of the armature conductor, ρ is the resistivity of the conductor (a function of temperature (T), and $J_a A_a = I_a$ = constant.

$$Q_T = k B_T^2 L' A_T \propto L' A_T$$

where k is a proportionality constant, L' is the length of the armature, and A_T is the cross-section area of the tooth.

The total armature conductor area (A_c) is related to A_a by the relation $A_c \propto T_p A_a$ where T_p is the number of turns, and the armature length (L') is related to the conductor length (L) by the relation $L' \propto L/T_p$. As a consequence of fixing r = 1, it is clear that $A_c = A_T$; and with D fixed, $A_c = A_T \propto d$ where d is the depth of the slots.

Combining the above,

$$A_a \propto \frac{A_c}{T_p} \propto A_c \frac{L'}{L} \propto L' d.$$

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Returning to the loss equations

$$Q_R \propto \frac{\rho}{A_a} \propto \frac{\rho}{L' d}$$

$$Q_T \propto L' A_T \propto L' d,$$

the third loss component is given by

$$Q_c = k B_c^2 t L'$$

where B_c is the flux density in the iron core and t is the thickness of the core. Balancing the flux in the core with the flux in the gap,

$$B_c t L' \propto B_g D L' ;$$

$$\therefore \quad B_c t = \text{constant}.$$

Consequently,

$$Q_c \propto B_c^2 t L' \propto L'/t.$$

The weight of the system is composed of two parts: the motor weight and the refrigerator weight.

$$W_{system} = W_{motor} + W_{refrigerator}$$

where the motor weight is a function of its length and diameter and the refrigerator weight is a function of the losses and the temperature.

The following table (Table XVII) lists the effects of changing the various independent parameters on machine weight and losses.

Table XVII

Effect of Parameter Variation on Cryogenic Machine Design *

Independent Variables				Dependent Variables			
L'	d	t	T	Q_R	Q_T	Q_c	W
+	0	0	0	−	+	+	+
0	+	0	0	−	+	0	+
0	0	+	0	0	0	−	+
0	0	0	+	+	0	0	0

+ indicates increase   − indicates decrease

* power, speed, voltage assumed constant

Design

In order to get a feeling for just where the cryogenic machines fit in with respect to equivalent superconducting machines, a specific design is considered with specifications as follows:

Four motor/generators

3000 horsepower
1200 rpm

One refrigeration system

This system is analogous to system D of Section 6.1 of this report.

For this system the optimum operating temperature is about 40° K. The resulting final design data are given in Table XVIII. The total weight is more than a factor of two times the equivalent superconducting system weight.

Table XVIII

Cryogenic Transmission System Data

Motors (4)

3000 hp; 12,000 rpm; 4-pole; 2000 vrms
Current density 18×10^3 amperes per inches squared

Flux density in gap		15 kg
Operating temperature		40° K
Overall dimensions		16 in dia x 12 in long
Motor weight		670 lbs
Losses	$I^2 R$	528 watts
	Teeth	258
	Core	1335
	Misc.	324
	Total	2445 watts

Refrigerator (1)

Capacity	9780 watts
Weight	523 to 880 lbs

Total System Weight	3212/3560 lbs
Including 10:1 reducers	4864/5212 lbs
Total weight of equivalent superconducting system (System D, Section 6.1)	2201/2668 lbs

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The advantages and limitations encountered in adapting superconducting electrical machinery to replace the mechanical power transmission system in aircraft are presented. Major components and system arrangements are evaluated and compared relative to weight, volume, efficiency, reliability, readiness, and cost. The superconducting systems when used in high total power applications are competitive on the basis of weight and efficiency, occupy a greater volume, but are more reliable when compared with the equivalent mechanical system.

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